Particulate matter pollution from aviation: Effective measures for changing the course of longstanding environmental injustices

Pedro Piris-Cabezas [a], Glenda Chen [b], Kate Roberts [c], Jeremy Proville [d]

[a] Environmental Defense Fund, Madrid, Spain (corresponding author, mail to: ppiris@edf.org)
[b] Environmental Defense Fund, Raleigh, NC, USA
[c] Environmental Defense Fund, San Francisco, CA, USA
[d] Environmental Defense Fund, New York, NY, USA

Highlights

- Adopting federal jet fuel regulations to set the aromatic content to as close as possible to 8% can slash particulate matter (PM) pollution in the near term –by as much as 50 to 70% in some instances—, while ensuring adherence to existing flight safety certifications and fuel quality specifications.
- While alternative fuels hold potential for reducing PM emissions, only cleaner conventional jet fuel has the potential to deliver short-term benefits.
- Delivering lower aromatic content jet fuel implies the optimization of existing refinery operations for available jet fuel blend stocks to meet lower aromatic content specifications in the aggregate.
- The cost of setting aromatics to just above 8% in jet fuel would amount to an increase in jet fuel cost for air carriers well below 2%, or less than 0.4% of their total operating expenses, but any potential cost increases should be significantly tempered with fuel efficiency gains.
- Absent swift federal action in the United States, state-level regulatory authorities could implement jet fuel regulations that avoid running afoul of any of the relevant federal statutes or doctrines.
- Jet fuel regulation can address aviation's environmental injustices in and around airports, while simultaneously contributing to improve regional and global air quality, and to mitigate aviation's non-CO_2 climate impacts.
- Geospatial proximity mapping suggests a nationwide pattern of socioeconomic and racial/ethnic disparities in exposure to aircraft pollution in airport-adjacent residential communities across the United States.
- Census estimates from a sample of 64 large- and medium-hub U.S. airports give nationwide totals of 5.8 million and 16 million residents for 10km x 5km and 20km x 5km exposure zones oriented along airport runways to reflect flightpaths.

Abstract

Aircraft gas turbine engines emit substantial quantities of fine particulate matter ($PM_{2.5}$) pollution, notably at sizes in the ultrafine particle (UFP) range smaller than 100 nanometers. In addition to the contributions of $PM_{2.5}$ emissions to degrading regional air quality, impacts of direct exposure in and around airports are an important public health concern. Regulatory controls on $PM_{2.5}$ pollution are crucial to achieving a meaningful and equitable improvement in public health outcomes. Aircraft $PM_{2.5}$ emissions are largely influenced by the aromatic content in jet fuel and engine design. To achieve near-term reductions while maintaining compliance with existing airworthiness certifications, the U.S. government should prioritize the adoption of regulations limiting the aromatic content in jet fuel to 8%, or as close as practicable. This approach would reduce PM emissions in and around airports, while also delivering significant regional and global air quality improvements and contributing to the reduction of aviation's non-CO_2 climate impacts. In the absence of swift federal action, state-level regulatory authorities should take the initiative to implement their own jet fuel regulations. Such regulatory action will be a cornerstone in addressing aviation's environmental injustices. Occupational and residential proximity to aviation traffic translates to highly concentrated pollution exposure and associated health risks for certain populations. To assist regulators with documenting the necessary evidence to justify new rulemaking, we use geospatial proximity mapping to investigate whether the population demographics of airport-adjacent residential communities suggest a nationwide pattern of socioeconomic and racial/ethnic disparities in exposure to aircraft pollution across the United States. We analyze population statistics from a sample of 64 large- and medium-hub airports, defining the modeled exposure zone as a rectangle oriented along airport runways to reflect the mobile source flightpaths. Census estimates for these zones give nationwide totals of 5.8 million and 16 million residents in the 10km x 5km and 20km x 5km rectangles, respectively. We find that demographics in airport-adjacent communities reflect higher-than-expected proportions of census-designated racial/ethnic minorities, low-income families, and groups with limited access to high school education and English proficiency. Immediate and decisive action is imperative to change the course of these longstanding environmental injustices.

Keywords

jet fuel regulation; aromatic hydrocarbons; air quality; geospatial proximity mapping; population; demographics

1. Introduction

Aircraft engines combust fuel imperfectly and incompletely, emitting combustion side products derived from fuel impurities and high-temperature reactions with air molecules. Jet engine emissions consist of volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur oxides (SO_x), low molecular weight polycyclic aromatic hydrocarbons (PAH), particulate matter (PM), and metals, all of which have well-established toxicity profiles associated with adverse health outcomes. Among these air pollutants, fine particulate matter with aerodynamic diameters of 2.5 microns and below ($PM_{2.5}$) are especially dangerous to human health (Bendtsen et al., 2021; U.S. Environmental Protection Agency [EPA], 2019; Habre et al., 2018; Masiol et al., 2017; Rissman et al., 2013; Yim et al., 2015). Aromatic compounds, a significant component of jet fuel, are responsible for significant PM formation. Aromatics are hydrocarbons present in crude oil that contain a resonant benzene ring and range in molecule size from the smallest compound, benzene, to larger compounds such as toluene, xylene, and naphthalene. The number and mass of particles[1] emitted from aircraft engines depends largely on the aromatic content in the fuel, as well as engine design.

[1] PM mass concentration denotes the total mass of all particles in a given volume of air. PM number counts the quantity of individual particles in a certain volume and emphasizes UFP.

PM hazards act through multiple physiological pathways. The EPA's Integrated Science Assessment (ISA) of PM released December 2019 concluded that 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 (EPA, 2019). These risks are present even at dosages in compliance with criteria pollutant 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 (Health Effects Institute, 2016-2022). In the U.S., the testing range for $PM_{2.5}$ was less than or equal to 12.0 micrograms per cubic meter, the primary annual limit during the study years[2] under the National Ambient Air Quality Standards (NAAQS) (Dominici et al., 2022).

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 ultrafine particulate (UFP) matter in and around airports (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). When compared to particle size distributions from other mobile sources, aircraft's fingerprint tends toward the sub-20nm end of the $PM_{2.5}$ range (Austin et al., 2019; E. A. Riley et al., 2016; Stacey, 2019). UFP may pose greater danger than larger $PM_{2.5}$ fractions – some literature suggests that sub-100 nanometer 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 (Bendtsen et al., 2021; Lammers et al., 2020).

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 $PM_{2.5}$ (Yim et al., 2015). 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 (EPA, 2022). A recent reevaluation 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, with 1,610 in the U.S. alone (Eastham et al., 2024).

This paper is organized as follows. Section 2 offers a feasible course of policy action that could directly curb pollutant formation at its source in the near term. Section 3 examines the demographics of airport-adjacent residential zones with the hope that it will jumpstart the

[2] In February 2024, the primary annual standard was revised from 12.0 to 9.0 μg/m³. However, those testing conditions are still far cleaner than the 24-hour and secondary annual limits, which remained unchanged. Furthermore, the mean exposure level in Dominici et al. 2022 was 8.4 μg/m³, indicating that several data points lie below the updated primary annual standard. As such, the discussion is still relevant.

discussion on the environmental justice (EJ) imperative for accelerated action. Section 4 concludes.

2. Effective policy measures to curb PM pollution

The EPA adopted the latest PM performance standards for aircraft engine design in November 2022. These standards were not designed for improving air quality, but rather to prevent backsliding; the standards reflect the current state of technology and prohibit future aircraft engines from exceeding said emissions limits. The 2022 performance standards were developed to replace the old smoke number standard from 1981, building on the statistical relationship between the smoke number index and non-volatile PM concentration: if an engine passes the 1981 smoke number standard regulating smoke plumes, it should also pass the new PM limit by design of the stringency level.

These limited regulatory interventions to address PM emissions have focused solely on aircraft engine design, systematically neglecting the outstanding potential of jet fuel regulation as a valid and complementary strategy to significantly reduce PM emissions in the near term. Here we offer mechanisms for crafting an economically feasible fuel regulation to drive swift action in curbing the aviation sector's toxic pollution.

The rest of this section is organized as follows. First, we review the available technologies for reducing PM emissions (Section 2.1). Second, we examine the current U.S. regulatory framework for PM and identify its shortcomings (Section 2.2). Third, we propose a targeted policy mechanism with the greatest near-term potential to mitigate PM emissions from aviation, and we outline additional steps to further reduce emissions in the longer term (Section 2.3). Finally, we explore potential co-benefits associated with the proposed policy mechanism (Section 2.4).

2.1. Available approaches for reducing PM emissions

The aviation industry already possesses technologies that can help meet stricter PM standards. These include: (1) Cleaner aircraft engine combustors, and (2) employing jet fuel with lower concentrations of aromatics –including complex aromatics such as naphthalenes— (Moore et al., 2017; Voigt et al., 2021; Faber et al., 2022; Schripp et al. 2022; Durdina et al., 2021; Dischl et al., 2024). In addition, there are operational improvements that can reduce PM pollution, notably the concentrated dosage experienced by EJ communities. These measures include the optimization of taxiing and reduced thrust during takeoff operations (Ashok et al., 2017; Koudis et al., 2017).

Although no aircraft engine has been specifically designed to lower PM emissions (Jacob & Rindlisbacher, 2019), modern lean-burn and advanced rich-burn combustors designed for reducing NO_x emissions also demonstrate significant reductions in PM compared to many engines currently in service. While these NO_x-targeting engines may also offer PM emission reductions, the mere existence of the technology does not ensure widespread industry adoption in the short term. Regulatory mandates will be necessary to incentivize investment in the production and usage of new engine types. However, since technology-forcing engine regulations often apply only to new type manufacture and exclude in-service aircraft, the near-term impact of this approach would be limited.

Interventions focused on jet fuel regulations present an opportunity to significantly reduce PM emissions from both new and in-service aircraft in the near term. A regulatory constraint on jet fuel aromatic content could be met with either cleaner conventional jet fuel or synthetic non-aromatic alternative fuels. However, as further discussed below, only the former has the potential to deliver significant short-term benefits.

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 –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 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 takeoff; the same blend at low thrust conditions achieved as much as 60% decrease in PM concentrations (Durdina et al., 2021). 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% (Moore et al., 2017). 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 –with the largest reductions observed at idle and low power conditions (Schripp et al. 2022)—, and the aromatic content in the conventional jet fuel used in the blend. These conclusions are relevant both to low-aromatics conventional jet fuel and to blends that include aromatics-free synthetic alternative fuels.

When it comes to reducing aromatic content of conventional jet fuel, most researchers' attention has been directed to hydrotreating straight-run jet fuel[3], i.e., applying post-distillation upgrading to the entire kerosene-range atmospheric distillation cut. However, modern refineries also produce jet fuel blend stocks from routine upgrading and conversion processes such as hydrocracking, and these premium blending streams have reduced aromatic content (Hemighaus et al., 2007). The properties of a finished jet fuel blend depend upon the combined properties of all its source streams, which are themselves a function of operating conditions of the upgrading and conversion processes they are subject to. Such operating conditions can be optimized for a target aromatics 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.

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 content specifications in the aggregate. Figure 1 illustrates the different streams of blend stocks available for jet fuel production in a modern refinery. It also illustrates the interaction with other petroleum products. The relative

[3] See, e.g., Faber et al., 2022. Hydrotreatment refers here to the process designed to remove sulfur, aromatics and other impurities by processing refinery products at high temperature and pressure in the presence of hydrogen and a catalyst.

importance of the jet fuel blend stock streams is a function of crude oil characteristics, environmental constraints and market demand for petroleum products.

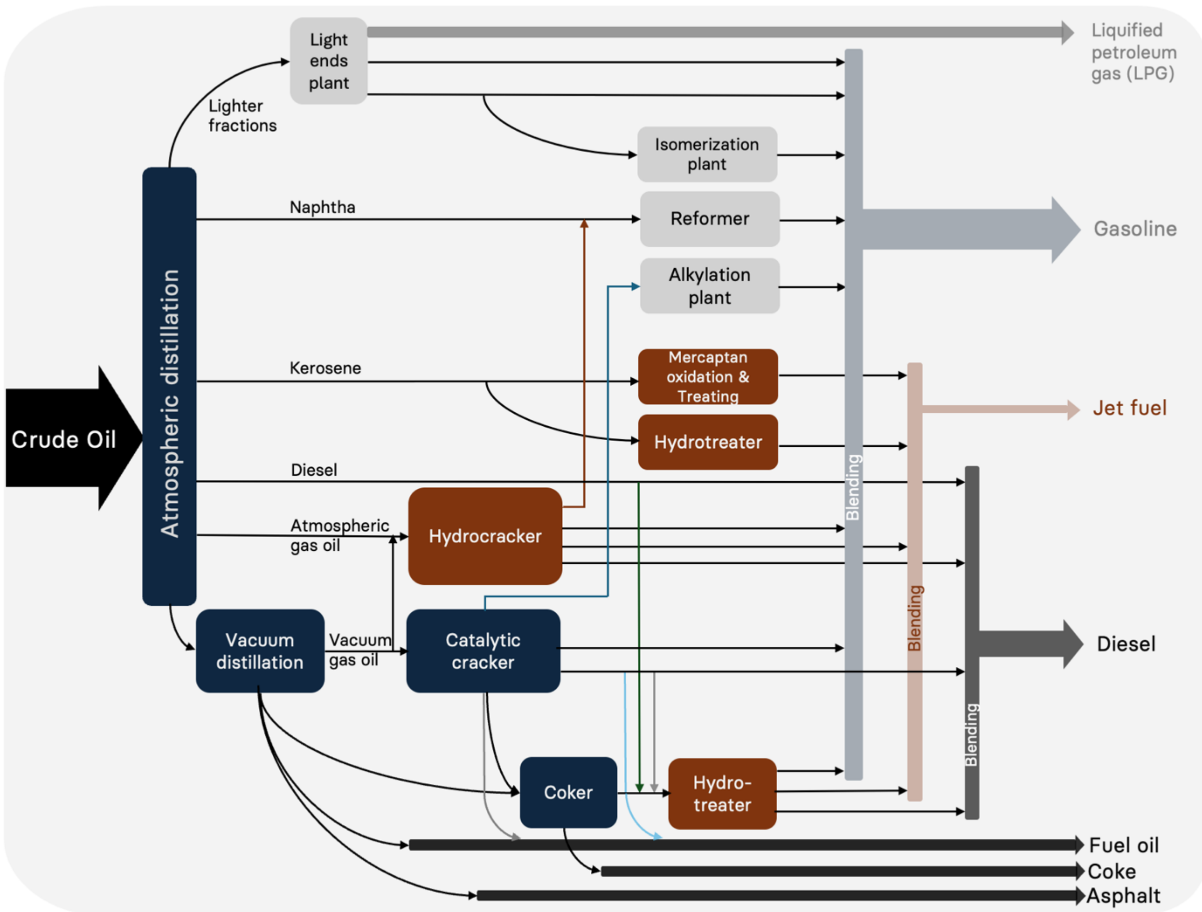

Figure 1. Available streams of blend stocks for jet fuel production (highlighted in brown) from all the various distillation, upgrading and conversion processes available in modern refineries. Illustrative figure adapted from Chevron Product Company's technical review on aviation fuels (Hemighaus et al., 2007).

As noted above, alternative fuels – including sustainable aviation fuels (SAF) — also hold potential for reducing harmful aviation PM emissions if (and only if) synthesized free of aromatics. However, unless a tighter regulatory cap on jet fuel aromatic content is enforced, there is no guaranteed reduction of aromatic hydrocarbons in fuel blends of synthetic alternative fuel and conventional jet fuel[4]; economic incentives and the headroom provided by the existing upper bound for aromatic content would cancel any potential gains. Furthermore, while high-integrity SAF[5] poses a natural avenue for reducing aromatics, its gradual scale-up means its benefits in the near term will be marginal.

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[4] According to ASTM International D7566 for aviation turbine fuel containing synthesized hydrocarbons, blending walls for synthesized hydrocarbons –including SAF—range between 5% and 50% of the fuel depending on the production pathway of the synthesized hydrocarbons.
[5] For a definition of high-integrity SAF, see Environmental Defense Fund's SAF handbook here: https://www.edf.org/sites/default/files/2022-08/EDF%20HIGH-INTEGRITY%20SAF%20HANDBOOK.pdf

2.2. Current regulatory landscape and its shortcomings

In November 2022, the EPA published the latest PM performance standard and test procedures (EPA, 2022). This standard focuses on engine design and aligns with the technology-following engine standards adopted by the International Civil Aviation Organization (ICAO) in 2017 and 2020. This PM standard is intended as an anti-backsliding measure that reflects current technology without driving advancement.

Unfortunately, this status-quo regulation delivers no immediate improvement in regional nor local air quality. Although the agreement was reached within the framework of the ICAO, it is ultimately a product of the U.S. government's active engagement and leadership. The adoption of the PM standards would not have been possible without the concerted efforts and agreement of the EPA, FAA and State Department. While this rule paves the way for more stringent standards in the future, notably integrated PM and NO_x standards –an approach championed by the U.S. in ICAO (EPA, 2022)— it fails to consider the crucial role that jet fuel regulation could play in reducing PM emissions and improving air quality in the near term.

Under Section 231 of the Clean Air Act (CAA),[6] the EPA has the statutory authority to either adopt a much more rigorous PM emissions standard than what was published or pursue alternative strategies to tackle PM emissions. However, the EPA argues in the 2022 rule that it has instead prioritized maintaining international regulatory uniformity over effectiveness, thereby allowing U.S. manufacturers of covered aircraft engines to remain competitive globally by adhering to ICAO's modest stringency requirements and obtaining timely domestic certification.

But even assuming the political feasibility of a technology-forcing PM engine standard entering into force in 2030 or soon thereafter, it would most probably have a limited reach -- applying only to new type design aircraft engine and excluding in-service aircraft. While engine standards are necessary, so too is another approach to PM regulation with different or broader scope.

Finally, in the PM rule, the EPA comments that the agency is "conducting a demographic analysis to explore whether populations living near the busiest runways show patterns of racial and socioeconomic disparity…Finely resolved population data (i.e., 30 square meters) will be paired with census block group demographic characteristics to evaluate if people of color, children, Indigenous populations, and low-income populations are disproportionately living near airport runways compared to populations living further away" (EPA, 2022). Our findings (Section 3) support the hypothesis on all four of these population characteristics and should assist regulators with documenting the necessary evidence to justify new rulemakings. Such regulatory action will be a cornerstone in addressing aviation's environmental injustices.

[6] "The Administrator shall, from time to time, issue proposed emission standards applicable to the emission of any air pollutant from any class or classes of aircraft engines which in his judgment causes, or contributes to, air pollution which may reasonably be anticipated to endanger public health or welfare." at 42 USC 7571(a)(2)(A)

As noted by the EPA, further analysis would help decisionmakers more fully (i) understand disproportionately high and adverse human health effects on people of color, low-income groups, and populations with underlying medical risks, (ii) characterize ambient particle size distributions from landing and takeoff (LTO) operations in and around airports, and relationships between different pollutants, or (iii) evaluate long-term impacts (Riley et al. 2021; EPA, 2022). However, these additional analyses will not diminish the urgency of taking action now, especially in light of the overwhelming evidence already available to the EPA.

2.3. A different approach to PM regulation

The EPA should prioritize an alternative regulatory approach to controlling PM emissions: reducing the aromatic content in jet fuel (Piris-Cabezas, 2022). This strategy can be implemented domestically, without waiting for action from the ICAO. To allow for a swift adoption, the EPA should build on the 2022 PM rule, notably on the assessment of PM impacts on air quality and health in Section III of the rule.

To achieve near term PM reduction outcomes, any alternative approach would need to be compatible with existing airworthiness certification as well as consistent with Section 231(a)(2)(B)(ii) of the CAA, which precludes approaches that increase noise or adversely affect safety. That means that jet fuel regulation will need to set aromatic content to a level compatible with existing jet fuel specifications before embarking on a complete phase out.

2.3.1. Setting appropriate aromatic levels and conducting a preliminary cost evaluation

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%. 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 (e.g., ASTM International, 2021). The requirement for a minimum aromatic volumetric content of 8% in D7566 stems from the fact that certain synthetic fuels lack aromatics. Additionally, the most relevant synthetic fuel pathways are subject to a distillation slope requirement and a blending limit of 50%; the remainder is filled using conventional jet fuel. Since the aromatic content of conventional jet fuel is typically above 16% (Faber et al., 2022), a 50% blend with zero-aromatics synthetic jet fuel results in a final aromatic content above 8%, still aligning with ASTM D7566 specifications. These constraints are essential for maintaining fuel performance and ensuring compatibility with existing aircraft engines.

Thus, setting the aromatic content at 8%, or as close to this target as practicable, is compatible with existing airworthiness certifications and consistent with the CAA. Although fuel refiners and blenders could already reduce aromatic content to as low as 8% without compromising aircraft seal compatibility nor jet fuel's performance specifications, industry practices typically aim for 15-20% (Faber et al., 2022) due to cost optimization incentives absent regulatory constraints.

Lowering the threshold past 8% requires further work to ensure safety, and promising avenues exist. A complete phase-out of aromatics is possible provided that in-service aircraft have sufficient time to adapt using fresh elastomer seals; seals that have not yet been exposed to high-aromatics fuel content appear to perform acceptably without aromatics (Holladay et al., 2020). Otherwise, cycloalkanes can substitute for aromatics in achieving sufficient elastomer seal swell to prevent leakage while minimizing PM emissions and increasing energy content (Landera et al., 2022).

The cost of reducing aromatics to just above 8% (a 50% reduction) while minimizing naphthalene content[7] and removing sulfur compounds has been estimated to amount to an increase in jet fuel cost for air carriers of around 2% (Faber et al., 2022), or 0.4% of their operating expenses.[8] These estimates assume that jet fuel is hydrotreated using hydrogen from steam-methane reforming, and that jet fuel producers are in a position to pass through 100% of any cost increases to air carriers.[9] The reduction in aromatic content through such hydrotreating assumptions would come with a greenhouse gas (GHG) emissions penalty of around 2.5% compared to the average total lifecycle GHG emissions of fossil jet fuel (Faber et al., 2022).

Even then, these cost estimates represent a conservative upper bound for modern refineries. The jet fuel cost increase of 2% captures the increment in operational costs of optimizing process conditions and inputs –especially hydrogen— of existing hydrotreating and steam reforming units 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 have reduced aromatic and sulfur content (Hemighaus et al., 2007), bringing down the overall cost of producing low-aromatics jet fuel blends as compared to relying on only hydrotreating of straight cuts.

Furthermore, any additional hydrogen needed for hydrotreating could be supported by the Inflation Reduction Act (IRA), which offers substantial tax credits for clean hydrogen.[10] This would help further cushion potential production cost impacts and minimize GHG emissions penalties. As replacing aromatics with paraffinic molecules 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 (Holladay et al., 2020). However, at the same time, reducing aromatics also results in lower volumetric energy density, which might diminish the range gains for a given aircraft's finite fuel tank volume.[11]

2.3.2. Outline of next steps for regulatory action

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[7] Naphthalene is a subcategory of aromatic hydrocarbons with a double aromatic ring. Among the aromatics, naphthalene is understood to be a major contributor to combustion soot and black carbon (ASTM International, 2021).
[8] We derive the 0.4% estimate from 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. These estimates reflect average values over the past ten years.
[9] However, not all value chains conform with the assumed scenarios in Faber et al. where carriers bear the full burden of any additional costs.
[10] The Inflation Reduction Act provides for tax credits to produce clean hydrogen under Section 45V.
[11] Here, too, cycloalkanes may be available as substitutes. Cycloalkanes are less dense by volume than aromatics but denser than straight-chain paraffinic alkanes (Holladay et al., 2020).

First, the EPA and FAA should swiftly adopt jet fuel regulations that set the aromatic content at 8%, or as close to this target as practicable. Considering that controlling overall aromatic content will also result in naphthalene and sulfur content removal, jet fuel regulations should include provisions to ensure that these individual components are consistently regulated.

Jet fuel regulation should apply to all jet fuel uplifted in the U.S., covering both arrival and departure operations for domestic flights, and departure operations for international flights. For international flights landing in the U.S., international cooperation—whether through bilateral agreements or within the ICAO framework— would be necessary to harmonize regulations. Concurrently, the EPA and FAA should continue to promote advancements in cleaner combustor technology to maximize long-term environmental and public health benefits.

As a next step, the EPA and FAA should develop an implementation plan to phase out aromatic content as soon as it is technically feasible, while maintaining jet fuel performance specifications.

2.3.3 State-level regulatory action

In the absence of swift federal action, state-level regulatory authorities should move forward with implementing their own jet fuel regulations, particularly in jurisdictions with PM nonattainment areas near airports. State-level initiatives have the potential to produce meaningful outcomes: If the twelve U.S. states that commented jointly on the EPA PM ruling were to coordinate and set jet fuel aromatics at or near 8%, this would cover approximately 44% of the total jet fuel uplifted in the U.S. and thereby deliver significant air quality improvements across the country.[12]

No doubt, understanding the legal basis is a precondition for regulating jet fuel at state level. A thorough analysis offers a promising outlook: setting the aromatic content at or near 8% is unlikely to run afoul of any of the federal statutes or doctrines in question – Clean Air Act, Airline Deregulation Act, FAA Authorization Act, Foreign Commerce Clause, Dormant Commerce Clause, or Federal Aviation Act.

First, such state action would align with FAA's airworthiness certification regulations and would not interfere with exclusively federal areas such as the field of aviation safety. State-compliant jet fuel would still be compositionally similar to conventional jet fuel and subject to the same standard specifications concerning physical and chemical properties.

Second, state-level regulation would not discriminate against out-of-state interests nor prevent the federal government from speaking with one voice when regulating commercial relations with foreign governments nor affect airline prices, routes, or services. Indeed, resulting effects on airline prices –if any—should be very tenuous and greatly tempered by generous federal subsidies under the IRA and improvements in fuel efficiency.

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[12] Data Source: U.S. Energy Information Administration, State Energy Data System. Joint comment by the attorneys general of California, Connecticut, Illinois, Maryland, Massachusetts, New Jersey, New York, Oregon, Pennsylvania, Vermont, Washington, and Wisconsin: https://www.regulations.gov/comment/EPA-HQ-OAR-2019-0660-0203

Finally, any policy aimed at jet fuel aromatic content should be designed as a generally applicable regulation covering all relevant liquid fuels. This comprehensive approach should minimize trade-offs between different fuel types and thereby maximize protection for overburdened communities.

2.4. No-regrets policy

In addition to controlling aviation's PM pollution and delivering air quality improvements in the near-term –in and around airports but also at the regional and global scale (Yim et al., 2015; Eastham et al., 2024)—, fuel regulations can also reduce aviation's non-CO_2 climate impacts (Bier and Burkhardt, 2019; Kärcher, 2018; Märkl et al., 2024). Moreover, cleaner fuels could facilitate the development of advanced aircraft engine combustor technologies designed to reduce NO_x emissions (Holladay et al., 2020). This would not only mitigate the direct public health impacts of NO_x but also reduce other aviation-attributable pollutants, such as O_3, for which NO_x acts as a precursor.

2.4.1. Non-CO_2 climate impacts

The non-CO_2 climate impacts of aviation constitute a significant portion of aviation's current net climate effect (e.g., Lee et al., 2020; Burkhardt et al., 2018; Kärcher, 2018), with persistent aircraft condensation trail (contrail) cirrus clouds being one of the primary drivers (Lee et al., 2020). Where there are still knowledge gaps regarding contrails and contributions from various carbonaceous or non-carbonaceous PM types (e.g., Singh et al., 2024), soot particles are identified as the major constituent of contrail formation in engine exhaust. Soot serves 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 (Bier and Burkhardt, 2019; Kärcher, 2018).

Recent in-situ measurements of PM emissions and contrails from cruising aircraft burning paraffinic synthetic jet fuel have shown a significant reduction in both PM emissions (Dischl et al., 2024) and on ice crystals in contrails (Märkl et al., 2024). This suggests that aromatics control is also a viable pathway for mitigating radiative forcing from contrails, in addition to addressing toxic air pollutants in and around airports.

A complementary approach to reducing contrail cirrus involves using prediction models based on weather forecasts to adapt flight routes or schedules – whenever air traffic management and performance priorities permit— to avoid ice-supersaturated areas (e.g., Rosenow et al., 2018; Kölker et al., 2024). In the future, machine learning models leveraging satellite imagery could support measuring persistent contrails on a per-flight basis and establishing benchmarks for improving contrail prediction models (Geraedts et al., 2024). These advancements in information technology could also prove valuable in the context of measuring contrail avoidance strategies focused on jet fuel regulation.

In conclusion, jet fuel regulation represents a no-regrets policy for the protection of public health and welfare, without compromising other policy objectives. Such regulatory action will be a cornerstone in addressing aviation's environmental injustices while maximizing environmental and public health benefits.

To provide a more comprehensive understanding of aviation's environmental injustices in and around airports and to assist regulators with documenting the additional evidence to justify new rulemakings to regulate jet fuel, attention in Section 3 is directed towards the EJ dimensions of PM pollution.

3. Aviation's environmental injustices in and around airports

Airport workers are facing a major occupational hazard: Proximity to running jet engines is associated with heightened exposure to nano-sized particles and VOCs, and in turn with increased risks of disease, hospital admissions and self-reported lung symptoms (Bendtsen et al., 2021). Communities adjacent to aircraft LTO activity, especially on the landing side, are also exposed to concentrated pollutant release from flightpaths directly overhead (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). Furthermore, analyses of racial-ethnic exposure disparities across the U.S. have found that nearly all major pollution source types contribute systemically to higher exposure experienced by people of color than by white persons (Liu et al., 2021; Tessum et al., 2021).

EJ discussions centered on preventative health underscore that disparities between individuals' experiences are not just "random outcomes" sprung out of happenstance. Rather, structural inequities entrenched into systems for urban planning, social services, and civic participation have constructed a landscape of cumulative burdens for frontline communities, a landscape in which zip codes determine lifespans more strongly than do individual health habits (Solomon et al., 2016).

Researchers have extensively documented social determinants of health and wellbeing, including histories of redlining in city neighborhoods, racial barriers to economic opportunity, and discriminatory exclusion from meaningful civic participation or self-advocacy (Lane et al., 2022; Prochaska et al., 2014). These factors impede quality of life through artificially constraining access to material means (e.g. housing, groceries, income), essential public services (e.g. health care, telecommunications, transportation, voting, sanitation), and/or processes of negotiation for legal protection (e.g. town hall meetings, redress in discrimination cases, policy rulemaking dockets). These factors then indirectly or directly allow for in-service air, water, and noise pollution to accumulate in concentrated locations. Often, multiple long-term stressors impose disproportionate burdens repeatedly on the same communities across generations.[13]

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[13] Descriptors vary in definitions and usage – e.g. vulnerable, at-risk, marginalized, oppressed, disadvantaged, underserved, overburdened, etc. Often, the timescale of decades or centuries is implicit in the ways that EJ practitioners, researchers, and policymakers apply these terms. The federal Justice40 Initiative, for example, uses the umbrella term disadvantaged communities to refer to a combination of conditions faced by these subpopulations: underinvestment in social services, overburden from pollution, and marginalization from participation in decision-making processes.

These underlying risk factors for pollution susceptibility are acknowledged by regulators as well; The EPA's 2019 ISA used in both the 2020 and 2024 NAAQS rulemakings concluded that stratified analyses provide strong evidence for racial and ethnic differences in $PM_{2.5}$ exposures and related health risk (EPA, 2019). As noted in Section 2, the aircraft-specific rule for engine PM standards cites the ISA as well and notes these racial and ethnic disparities (EPA, 2022). However, gaps persist in transforming data into effective action.

Detailed studies of residential areas around Atlanta Hartsfield-Jackson, Seattle-Tacoma, and Boston Logan airports found poverty and racial/ethnic minority identity to be strongly linked to aviation pollution: populations with lower incomes and large percentages of people of color are more likely to be located in areas strongly affected by aircraft emissions (Johnson et al., 2020; Logan Airport Health Study, 2014; Rissman et al., 2013). Moreover, studies surveying multiple airports point to patterns of procedural inequities over time that have converged to produce current distributional injustices: over the four decades marking the rise of the jet age and the deregulation of the aviation sector, percentages of low-income, immigrant, and ethnic minority groups increased in airport-adjacent communities, likely influenced by push-pull effects (Woodburn, 2017). Nor have National Environmental Policy Act (NEPA) evaluation processes for airport permitting sufficiently detected or addressed injustices that proposed airport expansion projects would exacerbate (Woodburn McNair, 2020).

A window for action has opened in recent years with the growing push for the aviation sector to clean up its pollution, both GHG and non-GHG alike. Current public discourse on EJ has called society's attention to the ethical matter: all persons deserve the opportunity to live a healthy life (NPR, 2023; *We Birthed the Movement*, 2022; Fairley, 2021; White House, 2021). Meanwhile, data can bolster the legal basis for tightened regulation. Although some technical studies have undertaken in-depth examination of demographics and pollution burden at single airports, and others have conducted broad nationwide surveys, few have characterized nationwide trends of aviation-related inequities. With this analysis, we aim to contribute to decision-makers' technical understanding around differential health burdens related to jet engine exhaust pollution. We hope that this data reinforces the imperative for urgent government and industry action.

3.1 Proximity mapping: Demographics of airport-adjacent residential zones

To equip policymakers with the data needed to defend the adoption of jet fuel regulation, we designed a geospatial model of LTO pollution exposure zones to investigate the research question, "Who lives near airports?" This experiment tests the hypothesis that populations in the LTO exposure zone will exhibit a prevalence of marginalized demographic characteristics higher than the regional averages. We use American Community Survey (ACS) 5-year databases (2017-2021) from the U.S. Census Bureau to retrieve and recombine demographic statistics describing populations who reside in airport-adjacent exposure zones. Unlike earlier studies that generalize across pollution source sites using a standard circular buffer, we define a rectangular LTO zone oriented along each runway (Figure 2, n=218 runways) for each of the 64 highest-traffic commercial service airports in the continental U.S., Alaska, and Hawai'i (FAA, 2024). These 64 large-hub and medium-hub airports, per FAA's classification, have a combined activity accounting for 87% of total nationwide passenger enplanements in calendar year 2021 (FAA *Airport Categories*, n.d.) We then compare these estimates to control statistics, or "expected" regional demographics, in each respective county that intersects an airport-adjacent rectangle.

We find that demographics in airport-adjacent communities reflect higher-than-expected proportions of census-designated racial/ethnic minorities, low-income families, and groups with limited access to high school education and English proficiency. The total census population count in the exposure zones was 5.8 million and 16 million for the 10km x 5km and 20km x 5km zones, respectively. Cleaning up engines and fuel technology would therefore have a material bearing on quality of life for at least this many millions of people in the U.S.

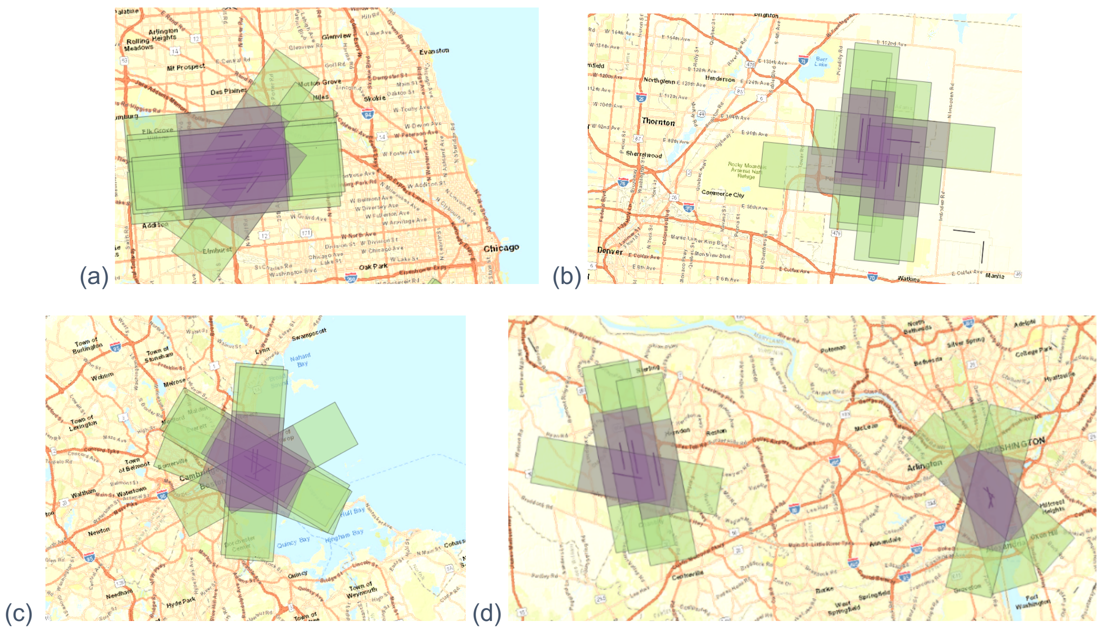

Figure 2. Modeled 10km x 5km (purple) and 20km x 5km (green) flightpath exposure rectangles at (a) Chicago O'Hare, (b) Denver, (c) Boston Logan, and (d) Washington Dulles and Reagan airports.

Of the 5.8 million people living within the 10km airport-proximate zones across the U.S., around 17 % of adult residents do not possess a high school degree, 16% live below the poverty line, and 66% identify as people of color, i.e., all individuals (including multiracial) who do not identify solely as White on the census. Although exact percentages for specific variables vary widely across locations, a majority of counties do show higher-than-expected demographic representation of those three key variables.

By comparing population statistics between the two rectangle model sizes, we investigated whether intensity of disparities is consistently related to distance. We found that relative deviation in representation was more pronounced at closer proximity for the categories Hispanic/Latino, limited English proficiency, and incompletion of a high school degree.

For a complete description of our methods, detailed modeling results and the caveats of the analysis see Appendix 1.

3.2. Mitigating future high-impact areas

Though location-agnostic aircraft and fuel interventions such as those described in Section 2 do complement local public health efforts, tighter federal and state regulation of aircraft and fuel will only partially address pollution for those residents already living in the airport-adjacent zone. To preempt future instances of creating new high-impact areas, local governments should thoroughly factor health impacts and sociodemographic profiles into assessments and permits for any changes in land use zoning near airports, particularly when spatial expansion and development is involved.[14] A localized understanding of atmospheric dispersion, residential settlement patterns, and community needs (Rissman et al., 2013) is essential to mitigate future high-impact areas and protect vulnerable populations.

4. Conclusions

The EPA's latest PM performance standard overlooked the significant potential that jet fuel regulation holds for reducing PM emissions and improving air quality. Since aircraft engine PM pollution is largely driven by the aromatic content in jet fuel, the EPA and FAA should prioritize a regulatory strategy centered on reducing these compounds.

Implementing regulations to reduce the aromatic content to approximately 8% would deliver near-term reductions in PM emissions, while still adhering to airworthiness certifications, CAA requirements, and performance standards. Further reductions would necessitate the development of additional strategies that uphold safety and fuel performance specifications. In parallel, the EPA and FAA should continue supporting advances in cleaner combustor technologies to maximize long-term environmental and public health benefits.

Fuel regulation targeting jet fuel uplifted in the U.S. can be effectively implemented through existing federal regulatory authority, building on the framework provided by the latest PM rule. This approach avoids the need to wait for international action at the ICAO level, enabling immediate domestic progress in reducing emissions and improving air quality. Full coverage of fuel burn, including international flights landing in the U.S., will require international cooperation to harmonize fuel regulations. In the absence of swift federal action, state-level regulatory authorities should take the initiative to implement their own jet fuel regulations to protect populations exposed to toxic pollution.

Delivering jet fuel with lower aromatic content implies the optimization of existing refinery operations to ensure that blend stocks of available streams for jet fuel from the various distillation, upgrading and conversion processes meet lower aromatic content specifications in the aggregate. Targeting total aromatics to just above 8% will also minimize naphthalene

[14] Approvals for airport expansion and development projects are the purview of the FAA. However, local authorities handle land use zoning in the surrounding areas. Both processes should incorporate a transparent evaluation of social impacts, including health. Both processes should comprehensively communicate findings to local residents and facilitate meaningful incorporation of community input before and throughout decision making. Current environmental impact assessments do not sufficiently capture human health or equity dimensions.

content and remove sulfur compounds. Any increase in jet fuel cost for air carriers should stay well below 2%, or 0.4% of their operating expenses.

Such regulatory action will be a cornerstone in addressing aviation's environmental injustices. There is indeed an ongoing disparity in population groups' proximity to aircraft emissions from the busiest runways. Residents near airports bear a disproportionate share of the pollution burden from aircraft flying directly overhead. Using a novel buffer shape to reflect mobile emission along aircraft flightpaths, proximity mapping analysis finds that these communities' demographic makeup shows a high representation of minority racial/ethnic groups, some facing linguistic barriers, lower incomes, and reduced access to formal education relative to population averages in their local counties. Therefore, it is highly likely that airport pollution burden and its consequent health hazards have historically been –and continue to be— disproportionately borne by disadvantaged communities. Absent intervention, these environmental injustices will continue for current and future generations. As such, regulatory controls on PM pollution are essential if we are to effect a meaningful and equitable shift in the trajectory of public health.

While further analysis would deepen understanding of health impacts on vulnerable populations, particle size distribution from LTO operations, pollutant interactions, and long-term consequences, these research questions do not ease the urgency for immediate action. With well-crafted regulations, the aviation industry can promptly address longstanding environmental injustices in and around airports, while simultaneously delivering crucial regional and global air quality improvements and contributing to the reduction of non-CO_2 climate impacts.

Acknowledgments

Thanks to Adam Gold, Ramon Alvarez, Maria Harris, Rachel Marston, Courtney Grimes, Ananya Roy and Anna Stratton for their discussion input and technical support. This work was generously supported by ClimateWorks Foundation and David Peyton.

Appendix 1. Proximity mapping

A.1 Methods

Our model strives to capture both geographic spread and context-relevant directionality. Shape and size choices for the modelled exposure area were informed by a combination of previous models found in literature, each based on its own definition of "airport-adjacent community."

The drawn polygon anchors to the global positioning system (GPS) coordinates of each airport runway and is constructed to reflect a smattering of flight paths, like highways in the sky projected down to ground level. This is analogous to mapping exercises that use stationary roadway footprints to approximate mobile pollution, as the exhaust itself emanates from mobile engines but along predictable tracks. These low-altitude segments of flightpaths are zones of direct exposure for people on the ground even before accounting for complex wind transport. Because human lung exposure to airborne particles takes place very close to the ground, mentions of "landing" or "reaching the ground" refer to the PM's arrival at this near-ground air layer.

Two main contributors to particle motion in the $< x, y >$ horizontal determine particles' landing spot: first, the engine coasting over the approach flightpath at low altitude, and second, wind transport. The relative dominance of either factor over the other is not well characterized in literature, as wind currents are highly sensitive to spatial and temporal variation. In this study, our geographic information system (GIS) model defines the exposure polygon based on engine travel along flightpaths; the LTO flightpaths are more definitively traceable and clearer to visualize than wind transport. The wing lift physics of downward air vortices also suggests that for particles to be deposited in a given (x, y) geolocation, vertical mixing in $< z >$ contributes with less time delay than does horizontal dispersion (E. A. Riley et al., 2016). Furthermore, LTO activity can serve as a reasonable proxy for wind direction anyway, since runway footprints are designed to align with prevailing winds for optimal flight aerodynamics.

A.1.1 Exposure zone shape

For simplicity in this initial study, we chose a time-static shape generalizable across diverse geographies, seasons, and times of day. Multi-airport studies tend to choose circles of uniform radius that transpose from one geography to another (Kamal et al., 2022; Lin et al., 2008; Woodburn, 2017; Woodburn McNair, 2020). Although the circle buffer is common in health studies and easily replicable for long lists of coordinates, this shape presents shortcomings in depicting LTO-related pollution. Whereas toxins from oil wells or industrial factory facilities typically travel through soil and ground/surface water in a diffuse radial wavefront from the center of origin, hazardous PM from in-flight aircraft is released in a discrete trajectory traced by the moving engine.

Mobile sampling data in the literature indicate spatial axes along which to analyze pollution burden. In case studies at LAX and at SEA-TAC, the gradient takes several miles to drop off. This presents a strong case for elongated geometry along the flight approach path: not only does the zone of PM exposure clearly extend beyond the runway and airport envelope, but it also reaches farther 'longitudinally' along the flightpath axis than 'sideways' along the transverse axis.[15] Therefore, we use in our model a rectangle with noticeably elongated length-to-width aspect ratio. Each GIS polygon is pegged to its corresponding runway.

Further support for this model assumption can be found in single-airport or single-region studies with fine-tuned design elements. Pollutant roses and conditional probability plots correlating particle number concentration (PNC) measurements with peak flight hours and wind direction suggest that an airport's pollution footprint is composed of buoyant exhaust plumes and matches runway layout and orientation (Chung et al., 2023; Hudda et al., 2016).

EPA researchers have used a somewhat descriptive method to highlight the directionality of LTO activity: compare demographics in "end-of-runway" semicircular end cap buffers to those in the whole runway buffer. This method and its findings informed the 2023 endangerment finding for leaded aviation gasoline (Clarke, 2022; EPA, 2023; Feinberg et al., 2016). However, the maximum distance of the endcap from the runway boundary along the flightpath axis was no farther away than the maximum distance along the transverse axis.

A.1.2. Exposure distance

We model LTO flightpath zones using two rectangle lengths for sensitivity comparison (Figure A1.1), 10 km and 20 km, while the width is held constant at 5 km.

The primary justification for these dimensions is based on findings from mobile transect monitoring at LAX and SEA-TAC. Even after differentiating between airport contributions and roadway contributions according to particle diameter, MOV-UP found samples of high airport-attributable UFP concentrations as far as 8-11 miles away from SEA-TAC's runways. Likewise, mobile transects performed downwind of LAX runways measured strikingly elevated concentrations at 10-16 km away (Austin et al., 2019; Hudda et al., 2014).

PM sampling at fixed sites near various airports measured ranges of particle concentrations on the order of five times the background level within 10km distances (Harrison et al., 2019; Hudda et al., 2014; Hudda et al. 2016; Keuken et al., 2015; Shirmohammadi et al., 2017). The literature base also reports elevated risks to respiratory, cardiovascular, and fetal health as far away as 15 km from large airports in Los Angeles, Boston, New York, and Amsterdam (Habre et al., 2018; Lammers et al., 2020; Lin et al., 2008; Logan Airport Health Study, 2014; Wing et al., 2020).

In this model, we define a conservative zone boundary for generalization to large and medium hub airports. At airports like LAX and SEA-TAC with extensive pollution zones documented, this smaller boundary still provides meaningful information as it is a subset of the full exposure zone.

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[15] This assumption could be more strongly validated if more mobile monitoring datasets of this type were available. The transect method is time intensive on data collection, hence why it is not yet replicated at many airports.

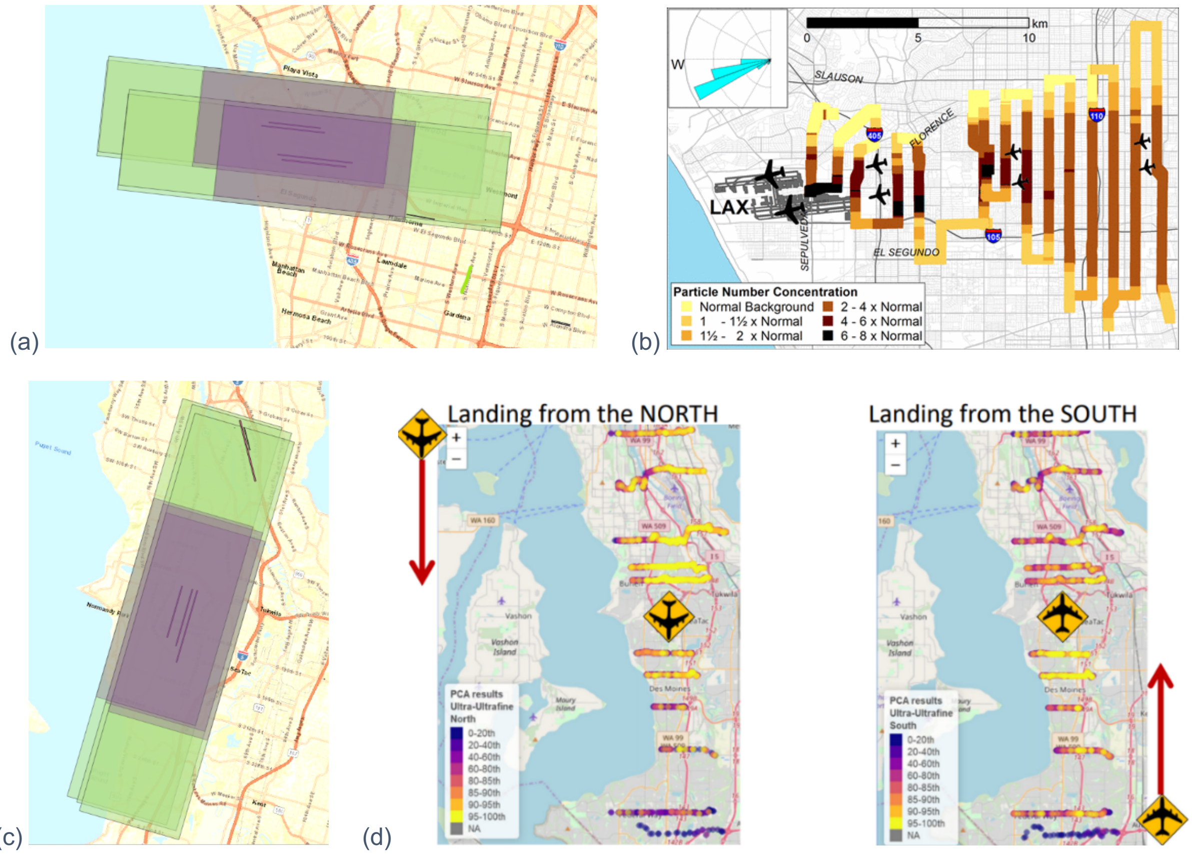

Figure A1.1. Flightpath zone rectangle lengths (a),(c) are based on mobile sampling data at LAX and at SEA-TAC (b),(d) (Hudda et al., 2014).

A.1.3. Airport sample selection

The list of airports was constrained to large and medium hubs so that the generalized assumption of exposure zone size could reasonably hold across the sample set. Small hub and non-hub airports with lower traffic are unlikely to have the same order of magnitude of post-combustion PM as major hubs like LAX and SEA-TAC. Furthermore, this selection of 64 airports, totaling 218 runways, covers commercial service but not general aviation airports. Gasoline-powered piston aircraft have engines distinct from those of kerosene-powered jet aircraft and are thus subject to separate regulations (EPA, *Regulations for Lead Emissions*).

A.1.4. Demographic estimation

Demographic statistics were retrieved from the tracts in the rectangles using a method originally designed to characterize populations residing adjacent to oil and gas well point sources (Proville et al., 2022). We selected a list of population characteristics across racial-ethnic composition, key socioeconomic metrics, and pre-existing health risk factors to investigate links of residential proximity to each variable. From the most recent 5-year ACS dataset covering years 2017-2021, the sociodemographic variables retrieved were: race/ethnicity categories American Indian and Alaska Native, Asian, Black or African American, Hispanic or Latino, Hawaiian and other Pacific Islander, White, no high school education, limited English, children under age 5, elderly over age 64, below poverty line, median family/household income (U.S. Census Bureau, 2022). The category People of Color represents all individuals (including multiracial) who do not identify solely as White on the census.[16] Other indicators of underlying risk and how the body may respond to additional air quality impacts, retrieved from Centers for Disease control and Prevention (CDC) PLACES, were: lack of health insurance, smoking, and disease rates for high blood pressure, cancer, asthma, coronary heart disease (CHD), chronic obstructive pulmonary disease (COPD), and stroke (CDC, 2023).

Using the rectangular GIS polygons as boundaries, demographic statistics are retrieved and recombined for county spatial resolutions. (National comparisons are also taken as a "reference baseline" but do not account for, e.g., the urban-rural divide in population profiles.) Each rectangle's surface area may cross county lines. Each airport also has multiple runways with overlapping rectangles; therefore, the union of sets is taken so as to count residents in the intersection area only once per person. Setting the analysis unit at the census tract geographic resolution (rather than, e.g., block group level) equilibrates between data availability, minimizing signal-to-noise ratio from margins of error, accuracy of estimates, and depth of demographic insight (Proville et al., 2022).

Due to the relatively large size of the exposure rectangles, each zone contained multiple full tracts and intersected several more. Populations in partially intersecting tracts were counted via areal apportionment.

A.1.5. Comparison to local region at large

The estimate of each demographic variable's representation in the airport rectangles was compared with representation in each corresponding county, per the following formula:

$$e_{i,r,c} = 100\% \times \left(1 - \left(\frac{p_{i,r}}{t_r} \Big/ \frac{p_{i,c}}{t_c}\right)\right)$$

Where $e_{i,r,c}$ is the disparity ratio or relative deviation from expected population share; subscripts refer to characteristic i, in rectangle r or control county c; the ratio $\frac{p}{t}$ gives a percent reflecting the estimated number of persons p in the demographic group in a zone divided by the total number of persons t residing in the zone.

These comparative statistics are then tested for significance according to Census Bureau guidelines for 90% confidence, using the below z-score formula (which takes margins of error MoE rather than standard error):

$$z_{i,r,c} = \frac{\left|\frac{p_{i,r}}{t_r} - \frac{p_{i,c}}{t_c}\right|}{\sqrt{{MoE_{i,r}}^2 + {MoE_{i,c}}^2}}$$

[16] Thus, the percentages for White and for People of Color sum to greater than 100%. Individuals can self-identify as e.g. both Native Hawaiian/ Pacific Islander and White.

In Table A.1 we report the fraction of the n counties nationwide for which the local disparity ratio is significant ($z_{i,r,c} > 1$), as well as the fraction of counties for which the variable's representation is higher inside the exposure zone than expected for the county ($\frac{p_{i,r}}{t_r} > \frac{p_{i,c}}{t_c}$). National summary statistics $\frac{\widehat{p_{i,r}}}{t_r}$ and $\frac{\widehat{p_{i,c}}}{t_c}$ and their relative deviation $e_{i,n}$ in Table A.1 are computed via a summation of population counts in all k of the affected rectangles, compared against a summation of population counts in all their adjacent counties n.

$$e_{i,n} = 100\% \times \left(\frac{\sum_{r=1}^{k} p_{i,r}}{\sum_{r=1}^{k} t_r}\right) \div \left(\frac{\sum_{c=1}^{n} p_{i,c}}{\sum_{c=1}^{n} t_c}\right)$$

A.2. Findings

The total census population count in the exposure zones was 5.8 million and 16 million for the 10km and 20km zones, respectively. We find that demographics in airport-adjacent communities reflect higher-than-expected proportions of census-designated racial/ethnic minorities, low-income families, and groups with limited access to high school education and English proficiency. For instance, of the 5.8 million people living within the 10km airport-proximate zones across the U.S., around 17 % of adult residents do not possess a high school degree, 16% live below the poverty line, and 66% identify as people of color.

Overall, the dataset showed consistent patterns of disparities in representation between the airport-adjacent rectangle zones and the entire county intersected by these exposure zones. Percentages of non-white racial/ethnic groups were higher inside the exposure rectangle than in their respective counties for more than half the locations, as were percentages of limited English proficiency, lack of a high school diploma, and income below the poverty line (Figure A.1).

Only some county/variable pairs had a sufficiently large sample size or small enough margins of error for the comparison metrics to carry strong statistical power. Significance tests on an individual county basis showed a statistically conclusive disparity in proportion of people of color for 72% of counties. This figure drops modestly to 67% at 20 km.

Results for location/variable pairs vary widely across the country. For instance, in the 10km exposure zones surrounding Phoenix Sky Harbor International Airport, 15.26% (±1.38) of the population (total 57 000) identifies as Black, more than twice the percentage in Maricopa County; 31.38% (±0.96) of adults do not have a high school diploma, more than two and a half times the rate expected in the county; and 6.97% (±0.79) have limited proficiency in English, nearly three times the expected share. At Denver International Airport, 21.23% (±4.07) of the 1.2 million population residing in the 10km zone identifies as Black, more than two and a half times the proportion in Adams and Denver counties. Meanwhile, 1.99% (±1.17) of adults have limited proficiency in English, only two-thirds the expected rate, and high school education percentage is close to parity. At Hartsfield-Jackson Atlanta International Airport, out of 1.3 million residents in the 10km proximity rectangles, 24.87% (±2.78) of the population lives below the poverty line. And out of 84000 residents near Seattle-Tacoma International Airport, 3.48%

(±0.91) of the population identifies as Native Hawaiian or Pacific Islander, more than two and a half times the representation in King County.

Table A.1. Community demographics near airports (10km x 5km flightpath zone). Summary statistics of sociodemographic groups and baseline health conditions. Percentages inside flightpath exposure rectangles are compared to percentages in their respective counties, per the formulas given in Section A.1.

Population group	National population baseline (%)	Reference counties (%)	10km airport rectangle (%)	Fraction of counties with (rectangle %) greater than (control %)	Fraction of counties with significant disparity ratio $e_{i,r,c}$ (90% CI)
White	75.29	64.19	59.17	0.38	0.60
People of Color	39.9	55.95	65.12	0.70	0.72
American Indian / Alaska Native	1.73	1.36	1.46	0.56	0.01
Asian / Asian American	6.53	11.09	11.98	0.32	0.15
African American / Black	14.07	17.85	19.16	0.60	0.50
Hispanic / Latino	18.83	27.15	34.73	0.60	0.42
Native Hawaiian / Pacific Islander	0.43	0.69	0.84	0.45	0.03
Limited English	2.39	2.88	4.16	0.56	0.21
No high school degree	12.12	9.02	17.22	0.62	0.41
Living below poverty line	13.4	13.27	15.56	0.56	0.28
Children under 5	6.07	6.37	6.55	0.60	0.02
Adults 65+	15.68	13.80	12.85	0.30	0.36
High blood pressure	23.49	21.95	21.23	0.54	0.46
Cancer	4.92	4.44	4.02	0.36	0.65
Asthma	7.15	6.95	6.80	0.59	0.32
CHD	4.34	3.81	3.78	0.49	0.66
Stroke	2.44	2.28	2.25	0.57	0.69
COPD	5.09	4.31	4.30	0.61	0.54
Smoking	12.95	11.51	11.86	0.66	0.42

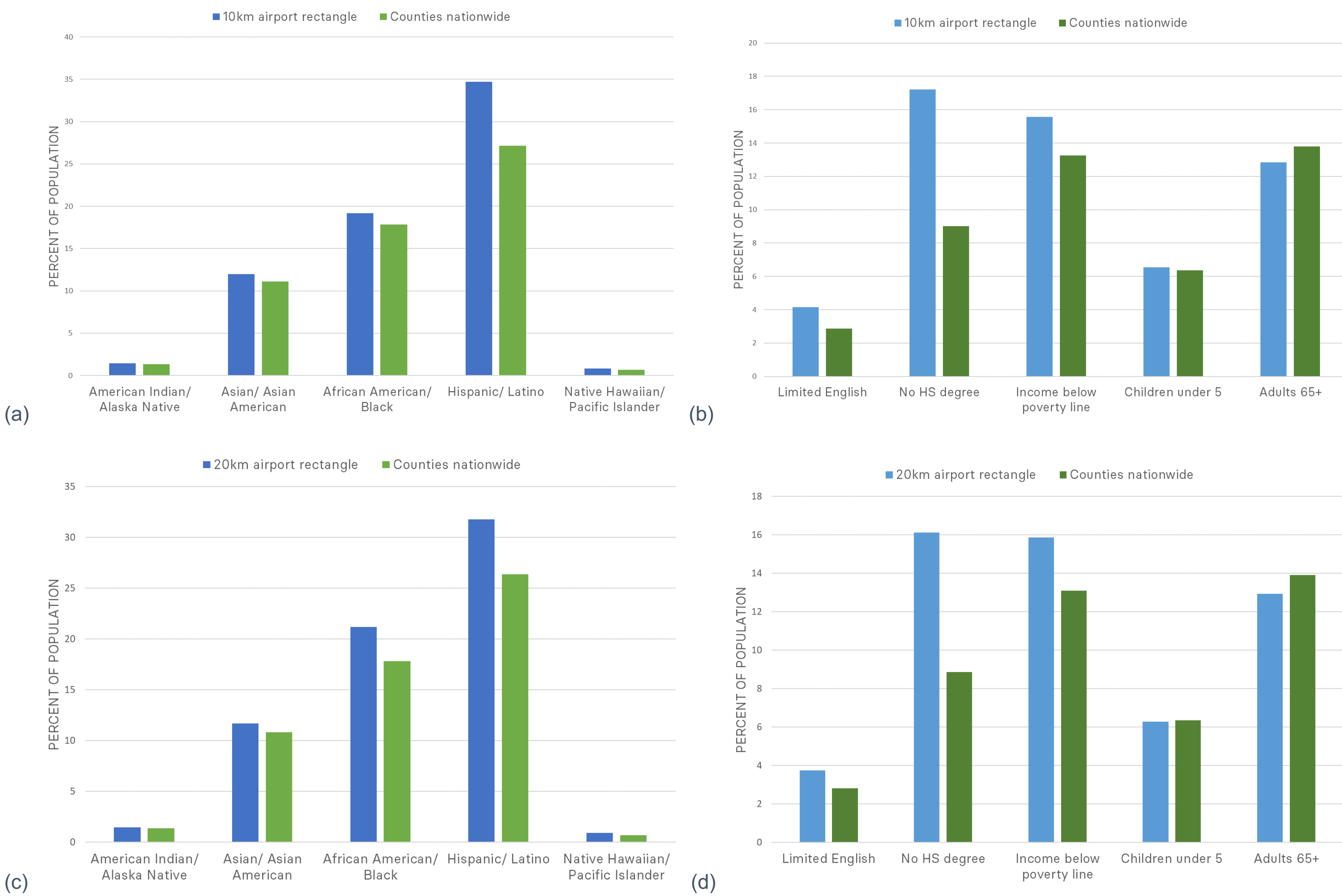

Figure A.1. Shares of sociodemographic groups inside (a), (b) 10km and (c), (d) 20km airport exposure zones compared to shares of population in their respective counties, aggregated nationwide. Racial/ethnic minority categories, as self-reported, are shown in (a) and (c). Socioeconomic factors are shown in (b) and (d).

Baseline disease rates were retrieved from CDC PLACES as a risk indicator of susceptibility to additional airport-induced health effects. Differences here were not evident between the runway rectangles and the control groups. However, this sampling took a residential nighttime basis rather than a daytime basis, as further explained in Section A.2.1.

Summary nationwide statistics are presented in Table A.1. The national baseline column offers a general frame of reference of the demographic makeup of the United States at large. Meanwhile, the sum of the control counties offers a second baseline reference more reflective of airports' local surroundings: airports are typically located near urban population centers, which attract more immigration than and exhibit different occupational activity profiles from rural areas. Thus, it can be expected that these rectangle zones would contain higher proportions of people of color and perhaps have different disease rates compared to the national average, simply by virtue of their peri-urban location – with or without high exposure to aircraft pollution. Taking the nationwide sum of control counties as the summary comparative reference is one way to account for this variation.[17]

By comparing population statistics between the two rectangle model sizes, we investigated whether intensity of disparities has a consistent relationship with distance. For the categories Hispanic/Latino, limited English proficiency, and incompletion of a high school degree, relative deviation in representation was more pronounced at closer proximity (Figure A.2).

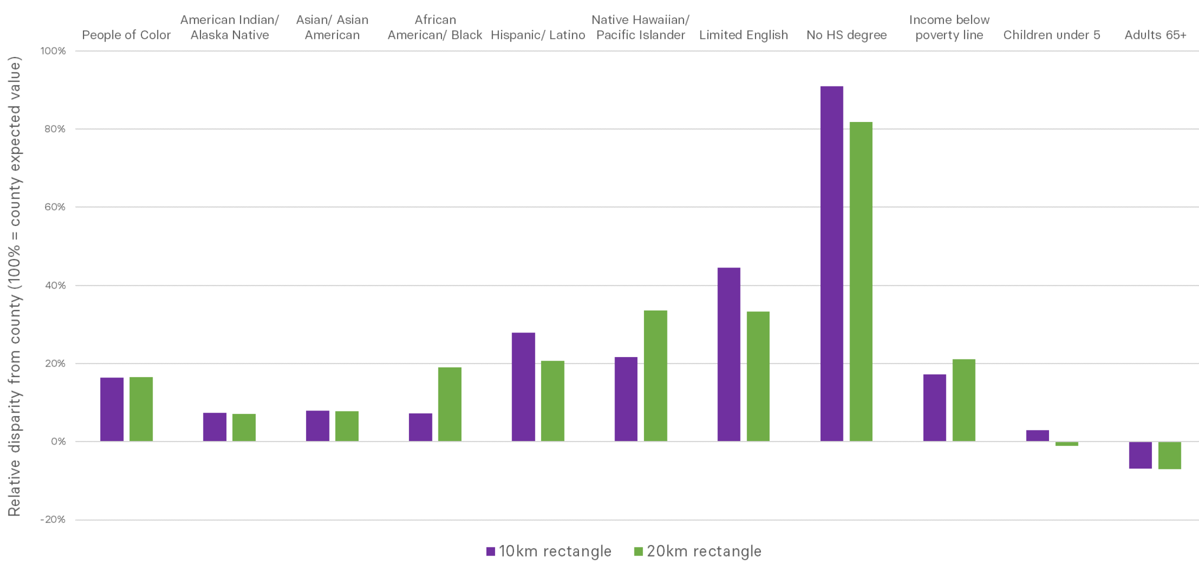

Figure A.2. Shares of sociodemographic groups and populations with baseline health risks, compared between 10km and 20km airport exposure zones.

[17] That said, this is no substitute for a local lens that compares a specific airport's proximate zone to in-county baseline statistics as well as examining any other local particularities.

The locally specific nature of the contrasts in each airport's corresponding county involves many historical factors, some unrelated to aviation, and therefore warrants further examination for specific places of interest. However, overlapping burdens do not exempt aviation from inquiry.

A.2.1. Analytical limitations

Measuring pollution burden is by nature inexact; the presence of particulate contamination forms a continuous but ununiform gradient with spatial and temporal heterogeneities. In addition, despite the best estimates of transport physics, individual random particles are subject to instantaneous, unpredicted motion in air currents. As such, any crisply delineated "exposure zone" on a map will leave uncounted some persons facing nontrivial risk, and it is entirely possible that a given individual residing just outside the zone boundary breathes a higher absolute particulate concentration than another individual inside the zone boundary. This study therefore does not attempt to "rank" the intensities of various individuals' exposure within airport-adjacent communities. We do not analytically state how much pollution each part of the zone receives, on the basis that each counted person likely experiences "relatively high" exposure and therefore deserves regulatory protection – the urgency of installing initial protections beyond business-as-usual is a discussion that need not be obscured by marginal variations in absolute pollutant concentration.

The exact quantity of particulate emissions in any given geography also varies depending on the amount of fuel burnt within a given time period. The fuel burn corresponds to frequency of overhead flights and to total traffic volume; data capturing either of the latter tends to be more readily accessible from open sources (e.g. FAA databases) than does data on fuel burn itself.[18] As a proxy for differentiating individual airports by volume of fuel burn, we limit the sample set to only large and medium hubs. This enables us to apply the same GIS "impact zone" definition to all airports in the sample set. The drawback of this modelling choice is that it does not compute population characteristics of communities adjacent to non-hub, low-traffic airports. Our model covers runways that host 87% of passenger enplanements, which leaves unsampled the residents in close proximity to the other 13% of nationwide commercial jet flight activity.

We did not weight the 180-degree portions of the map based on e.g. N-S flow versus S-N flow. Each runway is operable in either heads-tails configuration per the instantaneous wind direction, and airport custom is to land and take off with the aircraft's nose pointing into the wind. The landing phase of LTO cycle is generally understood to generate more pollution than the takeoff phase, due to less complete combustion reactions at reduced engine thrust (E. A. Riley et al., 2016). Though it is possible to subdivide flight activity by landing orientation and assign relative weighting to emphasize the landing-side emissions, this would be a computationally heavy task. Furthermore, residents on both 'heads' and 'tails' ends of a given runway experience pollution for some number of hours of the day, and therefore such an

[18] The exact emissions profile of an aircraft is also unique to each engine combustor type. Therefore, multiplying the number of takeoffs at an airport by an average emissions/fuel factor would give a reasonable approximation but would still homogenize all the operating aircraft in a fleet.

exercise would not change the fact that all airport-proximate residents deserve regulatory protection.

The census survey records individuals at their residential addresses, which does not capture their job locations where they spend a majority of daylight hours. Some of the population residing within the rectangle spends daytime hours at job locations outside the rectangle, and vice versa. Therefore, the residential sampling basis may in fact spread out the counts of airport workers and other commuters who experience high levels of aircraft pollution – and/or have high baseline rates of cardiovascular and respiratory disease that predispose individuals to further pollution sensitivity – but are registered at addresses outside the modeled exposure zone. People's likelihood of being outdoors is also higher during the day than at night. Future proximity mapping explorations could take source data from e.g. ORNL LandScan daytime population estimates.

In areal apportionment, the assumption of uniform population density and demographic profile in tracts is rolled up into summed counts in the given bounded rectangle. Edge effects raise accuracy concerns when a sampled portion of a tract contains very few or very many of the tract's total residents.[19] Updated iterations of the proximity mapping model that mask out non-residential polygons are in progress. While these iterations would still assume uniform population density over the residential surface area, the refinement would dramatically reduce uncertainties around diluted or over-attributed headcounts in the statistics derived from areal apportionment.

More broadly, there are many mediating variables between population characteristics, residential location, and health outcomes. While sociodemographic data can inform hypotheses about prevalence of co-located risk factors, our study does not perform dimensionality reduction analysis nor quantify relationships between covariates. Understanding cumulative burdens and meaningfully improving quality of life for pollution-adjacent communities requires understanding the interactions between the mediating variables on a local level.

A.2.3. Further considerations

Other literature has dedicated efforts toward quantifying pollution burden and correlating exposure with epidemiological outcomes at various spatial and temporal scales; such complementary lines of investigation would assist regulatory bodies in defining more stringent emissions and fuels standards.

The sensitivity analysis in this analysis varied only one parameter, rectangle length, with two representative values. Future studies at individual airports may want to calibrate the rectangle sizes to local particularities or alter the polygon shape. When not generalizing across a large sample set of facilities, one could choose the spatial zones specific to the local context. A regular geometric shape, such as a rectangle, somewhat artificially partitions neighboring residences on

[19] Tracts partially intersecting the rectangle are assumed to have uniform population distribution, such that a fraction of the tract's headcount is taken proportional to the surface area falling within the study rectangle.

the same street into an inside group and an outside group. However, tracts are typically defined by a grouping of similar characteristics or a neighborhood. Exposure zone edges could be handled by expanding the sample zone to include the whole surface area of each community intersecting the modeled airport exposure zone, rather than conforming to a regular geometric shape on the map.

Although further analysis would help decisionmakers fully understand disproportionately high and adverse human health effects on vulnerable communities, these additional analyses will not change the necessity for urgent action to address aviation's environmental injustices (Levy, 2021).

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