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Review Articles

A systematic review of the impact of commercial aircraft activity on air quality near airports

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ABSTRACT

Commercial airport activity can adversely impact air quality in the vicinity of airports, and millions of people live close to major airports in the United States. Because of these potential impacts, a systematic literature review was conducted to identify peer reviewed literature on air quality near commercial airports and assess the quality of the studies. The systematic review included reference database searches in PubMed, Web of Science, and Google Scholar, inclusive of years 2000 through 2020. We identified 3,301 articles, and based on the inclusion and exclusion criteria developed, seventy studies were identified for extraction and evaluation using a combination of supervised machine learning and manual screening techniques. These studies consistently showed that ultrafine particulate matter (UFP) is elevated in and around airports. Furthermore, many studies show elevated levels of particulate matter under 2.5 µm in diameter ($PM_{2.5)}$, black carbon, criteria pollutants, and polycyclic aromatic hydrocarbons as well. Finally, the systematic review, while not focused on health effects, identified a limited number of on-topic references reporting adverse health effects impacts, including increased rates of premature death, pre-term births, decreased lung function, oxidative DNA damage and childhood leukemia. More research is needed linking particle size distributions to specific airport activities, and proximity to airports, characterizing relationships between different pollutants, evaluating long-term impacts, and improving our understanding of health effects.

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1. Introduction

A recent study by Yim et al. [44] assessed global, regional and local health impacts of civil aviation emissions, using modeling tools that address environmental impacts at different spatial scales. The study attributed approximately 16,000 premature deaths per year globally to global aviation emissions, with 87% attributable to particulate matter under 2.5 µm in diameter ($PM_{2.5}$). The study concludes that about a third of these mortalities are attributable to $PM_{2.5}$ exposures within 20 km of an airport. While there are considerable uncertainties associated with such estimates, these results suggest that in addition to the contributions of $PM_{2.5}$ emissions to regional air quality, impacts on public health of these emissions in the vicinity of airports are an important concern. The study did not address relative contributions of specific components of $PM_{2.5}$, such as black carbon (BC), and size fractions, such as ultrafine particulate matter (UFP), which contribute to the adverse health impacts resulting from exposure to the $PM_{2.5}$ mixture [33].

A literature review was conducted in 2015 by the Airport Cooperative Research Program (ACRP; [18]), and focused on a wide range of peer reviewed sources, including university research as well as authoritative sources such as state agencies, the Federal Aviation Administration (FAA) and airport monitoring programs. Since the publication of the 2015 ACRP literature review, a number of studies conducted in the U. S. have been published which concluded that UFP concentrations are elevated downwind of commercial airports, and that proximity to an airport also increases particle number concentrations within residences. Particle number concentrations (PNC) are often measured as a proxy for UFP. This is because UFP is usually defined as particles with a diameter of less than 100 nanometers (nm), and most of the particle number concentration is below 100 nm. ACRP plans to update this review.

In addition to emissions from turbine engine aircraft, other sources, including piston engine aircraft, ground support equipment, and vehicle traffic all contribute to pollution levels in the vicinity of commercial airports. Turbine engine aircraft in particular emit large amounts of UFP. The UFP attributable to aircraft emissions has been associated with lung inflammation in individuals with asthma [8]. In addition, He et al. [9] found that particle composition, size distribution and internalized amount of particles all contributed to promotion of reactive organic species in bronchial epithelial cells.

Airport air pollution can also disproportionately impact sensitive subpopulations. Henry et al. [10] studied impacts of several California airports on surrounding schools and found that over 65,000 students spend 1 to 6 h a day during the academic year being exposed to airport pollution, and the percentage of impacted students was higher for those who were economically disadvantaged. Rissman et al. [25] studied $PM_{2.5}$ at the Hartsfield-Jackson Atlanta International Airport and found that the relationship between minority population percentages and aircraft-derived particulate matter was found to grow stronger as concentrations increased.

Although there is a significant body of research on air quality impacts in the vicinity of airports and the potential for adverse health effects from UFP, a systematic literature review of recent research on impacts of commercial airport emissions on air quality in close proximity to airports has not been conducted. Application of systematic review methods to air pollution issues was recently discussed in Lam et al. [20] Lam et al. point out that while a narrative review can provide a comprehensive overview of the scientific literature, a systematic review evaluates the literature in a systematic, transparent, and reproducible manner. This approach reduces the potential for bias and can help mitigate potential perception of “cherry-picking” data. Thus, we conducted a systematic review to achieve the following objectives:

- Identify peer reviewed literature on air quality near commercial airports
- Assess the quality of the studies, and
- Summarize evidence of pollutants most impacted and most likely health risks.

The focus of this systematic review was impacts of commercial airports dominated by jet aircraft activity; thus, studies that focused on ground service equipment or piston engine activity were excluded. Moreover, since this study did not focus on piston engine aircraft, emission impacts of lead due to its use as an additive in aircraft gasoline was not addressed.

Table 1
Inclusion/exclusion criteria.

Metric	Criteria	
	Include if:	Exclude if:
1. Pollutant type	Contains particulate matter or a chemical pollutant other than lead.	Does not contain particulate matter or a chemical pollutant. Or The pollutant is lead.
2. Data type	**On-Topic**[1] Contains a data type listed below: – Measured ambient air concentrations – Regression model ambient air concentrations – Dispersion Air Quality Modeling (Examples: AERMOD, CALPUFF, SCICHEM, ADMS-Airport, LASPORT)**Supplemental**[1] Does not contain an on-topic data type, but contains a supplemental data type listed below: – Airplane emissions, emission rates, and emission inventories – Indoor air concentrations (intrusion) – Personal air monitoring (residential or occupational) – Daily exposure estimates (mg/day) and doses (mg/kg/day) – Health impacts – Health risks	Does not contain an on-topic or supplemental data type of interest. Exclude examples include: – Regional modeling – Global modeling – Emissions and emission rate for non-aircraft activities (ground support)
3. Geographic location	U.S. or International	n/a
4. Airport type	Commercial and reliever airports (i.e., turbine or jet engine aircraft)	Not a commercial or reliever airport, such as military
5. Distance from airport	At and within 20 km of airport	>20 km from airport

[1] Included studies with an on-topic data type underwent data extraction and evaluation and were considered for inclusion in the summary of finding. Included studies with a supplemental data type were not further evaluated because they are considered out of scope.

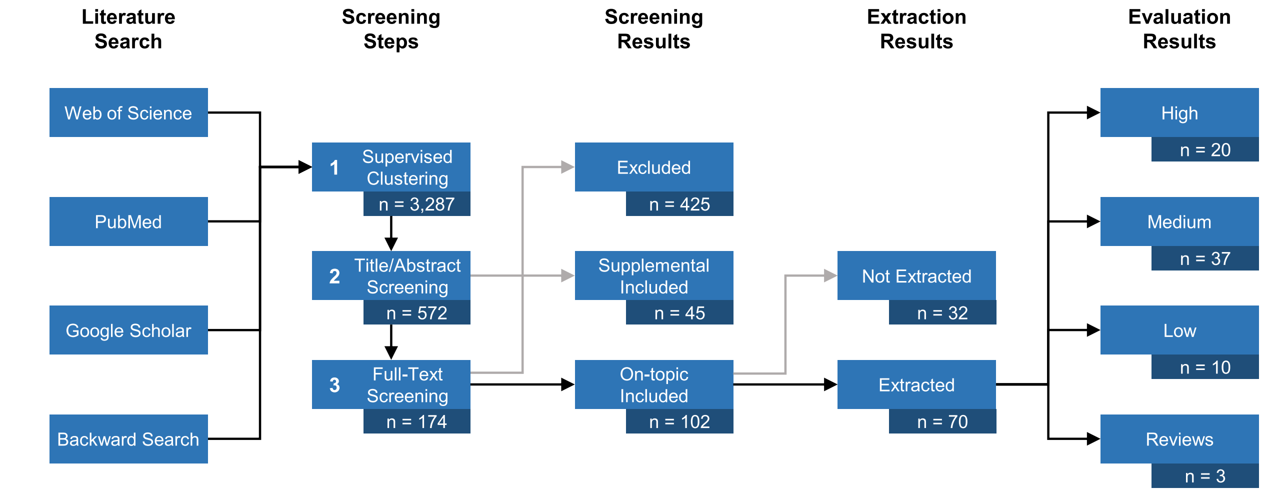

Fig. 1. Systematic review literature flow diagram.

2. Methods

The criteria used to select search terms and guide inclusion and exclusion of studies for this systematic review are presented below in Table 1.

The initial literature search was conducted using reference database searches in PubMed, Web of Science, and Google Scholar. Results from these sources were deduplicated to produce a unique set of 3,287 articles. An additional 14 references were also identified from relevant articles, for a total of 3301 references. The reference database search began with creating sets of keywords related to emissions, airports, and measurements based on the selection criteria in Table 1, with database-specific modifications as needed. For a citation to be included, the citation had to meet the search strategy for each keyword set. The basic limits applied for all databases included English language only and a date range of 2000–2020. For Web of Science, research areas were also limited to those most likely to contain relevant data. Following the literature search relevant literature was identified using the inclusion and exclusion criteria (Table 1) in three screening steps: supervised clustering using text analytics, title/abstract (TiAb) screening, and full-text screening. As depicted in Fig. 1, 70 studies were ultimately selected for extraction and evaluation.

The first screening step, supervised clustering, was conducted using ICF International's Document Classification and Topic Extraction Resource, DoCTER, which clusters studies that are expected to be more similar to one another using seed studies to inform automated text analysis of the titles and abstracts [38]. This screening step resulted in 558 articles that were predicted as "includes" based on relevance to the search criteria. The second screening step involved manual title/abstract screening of 572 references (558 articles from the initial literature search and 14 from background search) in the program litstream™ [20]. Articles were tagged as "On-Topic Include", "Supplemental Include", or "Exclude" per the criteria in Table 1. The screening was conducted by a single reviewer, with quality assurance review of approximately 10% of the studies by a second independent reviewer. At this step, 174 studies were tagged as on-topic "Includes". The third screening step, also conducted in litstream™, involved screening the full-text articles of the on-topic "Include" references from title/abstract screening. Portable document format (PDF) versions were obtained for 154 of 174 articles. On-topic references were re-classified as "On-Topic Include", "Supplemental Include", or "Exclude" as necessary. After full-text screening, the total number of articles classified as "On-Topic Include", "Supplemental Include", or "Exclude" were 102, 45, and 425, respectively.

Year	On-Topic Include: Extracted	On-Topic Include: Not Extracted
2000	0	0
2001	0	0
2002	1	0
2003	0	2
2004	0	1
2005	1	0
2006	5	1
2007	1	6
2008	5	0
2009	3	1
2010	3	2
2011	4	3
2012	4	2
2013	5	2
2014	3	1
2015	5	1
2016	11	2
2017	2	2
2018	2	3
2019	8	3
2020	7	0
Total	70	32

Fig. 2. Heatmap of studies by publication year.

While 102 references were tagged as "On-Topic Include" after TiAB or full-text screening, 70 U.S. and European articles were prioritized for extraction. Articles which were not extracted included those not available in PDF, some references which were more than 3 years old, and those identified from a backward search. In addition, some references which did not have PDFs to facilitate full text screening were also excluded. Extraction was conducted using litstream™ and involved recording the following information:

Table 2
Data quality criteria.

Metric[a]	Rating	Criteria
Data Reliability		
Source of Data (all)	Low	• Conference proceedings • Published journal articles from peer or non-peer reviewed journals that lack a scholarly format[b].
	Medium	• Pre-published peer-reviewed journal articles • Published journal articles that are not peer-reviewed, but follow a scholarly format[b]. • Non-peer-reviewed government reports or databases
	High	• Published peer-reviewed journal articles • Peer-reviewed government reports or databases
Not Reliable (all)	Unacceptable	• Newspapers and magazines containing news • Editorials, letters to the editor, book reviews
Relevance and Robustness		
Uncertainty Analysis (all)	Low	• Limited or no uncertainty analysis
	Medium	• —
	High	• Robust qualitative or quantitative uncertainty analysis
Temporal (all)	Low	• Sampling or modeling conducted over 0 to $<$ 3 months
	Medium	• Sampling or modeling conducted over $\geq$ 3 months to $<$ 12 months
	High	• Sampling or modeling conducted over $\geq$ 12 months (long term)
Spatial (all)	Low	• Off-airport only and not in immediate vicinity of aircraft
	Medium	• On-airport grounds, but not in immediate vicinity of aircraft
	High	• Immediate vicinity of aircraft, as well as on grounds and off airport
Background (all)	Low	• Analysis did not consider background levels.
	Medium	• —
	High	• Analysis considered background levels
Source Attribution (all)	Low	• No source attribution
	Medium	• Qualitative discussion of source attribution
	High	• Quantitatively attributed to specific sources at airport
Sampling, Analytical, and/or Modeling Methodology (all)	Low	Monitoring • Outdated data collection or analysis methods, or • Limited sampling and analytical methodology information provided.Modeling • Model is not widely accepted or is not described in enough to detail to assess applicability to scenario, or • Only limited model inputs discussed.
	Medium	• —
	High	Monitoring • Current data collection/analysis/modeling methods and • Robust sampling and analytical methodology information providedModeling • Widely accepted or sound model that is germane to scenario and inputs are well described as to their basis.
Model Evaluation (model only)	Low	• Limited or no model evaluation
	Medium	• —
	High	• Model has been evaluated through peer review, corroboration with monitoring data, and/or benchmarking against other models.
Reporting (all)	Low	• Only limited summary statistics (i.e., only mean and standard deviation or regressions) or incomplete summary statistics (i.e., missing number of samples) are reported and no raw data is provided.
	Medium	• —
	High	• Extensive summary statistics are reported or raw data is provided.

Table 3
U.S. Airports represented in this systematic review.

	City	Airport	Locid
CA	Burbank	Bob Hope	BUR
CA	Los Angeles	Los Angeles International	LAX
CA	San Francisco	San Francisco International	SFO
CA	San Jose	Norman Y Mineta San Jose International	SJC
CA	Santa Monica	Santa Monica Municipal	SMO
CT	Hartford	Hartford-Brainard	HFD
GA	Atlanta	Hartsfield-Jackson Atlanta International	ATL
MA	Boston	General Edward Lawrence Logan International	BOS
NJ	Teterboro	Teterboro	TEB
NV	Las Vegas	McCarran International	LAS
NY	Albany	Albany International	ALB
NY	New York	Laguardia	LGA
RI	Providence	Theodore Francis Green State	PVD
TX	Dallas-Fort Worth	Dallas-Fort Worth International	DFW
VA	Roanoke	Roanoke-Blacksburg Regional/Woodrum Field	ROA

- Study type: Primary or Review
- Supplemental data type: Emissions, Indoor Air, Personal Monitoring, Health
- Pollutant name
- Metric: Mass concentration, Particle number concentration (PNC), Particle size distribution (PSD)
- Ambient air data type: Monitoring, Dispersion Model, Statistical/Regression Model
- Health data type: Health Effect, Intake, Risk
- Is air quality impacted?
- Is health impacted?
- Airport Name, State, Country
- Sample location: On-Airport or Off-Airport
- Contextual information: Airport Operation or Aircraft Data (presence or absence)
- Source attribution: Take-off/landing, APU, run-up, other

A list of the extracted studies is included in the supplemental information. In addition, Fig. 2 provides a heatmap of studies by publication year. Articles that were extracted were also evaluated using the criteria in Table 2 to assess data reliability, relevance, and robustness. Each article was assigned an overall rating of High (n = 20), Medium (n = 37), or Low (n = 10). Review articles (n = 3) were not rated. It is important to remember that when integrating the articles into an assessment for a particular purpose, the importance of each individual criterion may vary. Also, these ratings were based on level of peer review and publication in a scholarly format; however, such ratings are subjective since publication decisions can be affected by decisions other than quality of investigations [40]. Furthermore, it should be noted that while we ranked studies with longer duration monitoring

Geographic Area	PM	UFP	PM2.5	PM2.5-10	Black carbon	CO	NO2	NOx	O3	SO2	13-Butadiene	Acetal-dehyde	Benzene	Naphth-alene	Formald-ehyde	Dioxins Furans	PAHs	Other
Brazil	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Canada	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	1
China	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Denmark	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
England	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Finland	0	1	0	0	1	1	1	0	1	1	0	0	0	0	0	0	0	1
Greece	0	0	2	1	0	2	1	1	0	1	0	0	0	0	0	0	0	2
Hungary	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1
Italy	0	2	1	2	1	2	3	3	2	3	0	0	1	0	1	0	2	2
Lebanon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Netherlands	1	1	0	0	2	1	1	0	1	0	0	0	0	0	0	0	0	0
Portugal	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Romania	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
Spain	0	2	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	1
Switzerland	0	1	0	0	1	2	2	0	1	1	0	0	0	0	0	0	0	2
Taiwan	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
The Netherlands	1	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0
United States	3	16	7	1	10	5	6	7	2	3	2	1	3	1	3	1	4	11
United States and Foreign	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
United Kingdom	0	3	3	4	3	2	4	7	3	2	0	0	0	0	0	0	0	2
Total	**7**	**30**	**18**	**11**	**20**	**20**	**20**	**24**	**12**	**12**	**2**	**2**	**4**	**1**	**5**	**1**	**7**	**25**

Fig. 3. Heatmap of studies by pollutant and country.

higher, studies that include extensive monitoring over a shorter time period can provide data with valuable insights.

3. Results and discussion

This systematic literature review corroborates many findings of the 2015 literature review conducted by the ACRP, in particular that UFP is highly elevated at the airport and persists downwind. Of the 70 selected studies, 33 were conducted in the U. S. These U. S. airports are listed in Table 3. In addition, Fig. 3 provides a heatmap of studies by pollutant and country. Twelve studies focused on one airport, LAX. Three were reliever rather than commercial airports (Santa Monica, Hartford, and Teterboro). Fifty of the selected studies included monitoring results, 21 included dispersion modeling, 18 included statistical analyses, and health effects were reported in 11. Furthermore, on-airport air monitoring and/or modeling was conducted for about 50% of the studies, whereas off-airport monitoring (within 20 km) and/or modeling was conducted in about 70% of the studies.

3.1. Ultrafine particulate matter

A number of early studies (2003–2011) found elevated UFP concentrations at fixed site monitor locations (Westerdahl et al., 2008, [41]; Zhu et al., 2011, [47]; Hsu et al., 2013, [11], 2014 [49]; Hu et al., 2009, [48]; Choi et al., 2013, [6]; Klapmeyer et al., 2012, [19]) . U. S. studies conducted in the last ten years showed similar results to earlier studies, although they tended to examine air quality further away from the airport using mobile monitoring or dispersion modeling (Hudda et al., 2014, [16], 2016 [15], 2018 [13], 2020, [12]; Hudda and Fruin, 2016 [15]; Riley et al., 2016 [24]; Yu et al., 2019 [45]; Shirmohammadi et al., 2017 [28]). These studies focused on Los Angeles International, Hartsfield-Jackson in Atlanta, and Logan Airport in Boston. Several of these studies [16,28,12] showed concentrations under landing approach paths several times background concentrations. Similar results were found outside the U. S. [17,22,23,50]). Since this review, three more studies with similar findings have been published [2,32,46].

Hudda et al. [13] investigated PNC inside and outside 16 residences in the Boston metropolitan area. They found elevated PNC within several kilometers of Boston Logan International Airport (BOS). They also found that aviation related PNC infiltrated indoors and resulted in significantly higher indoor PNC. In another study in the vicinity of Logan airport, Hudda et al. [14] analyzed PNC impacts of aviation activities. They found that at sites 4.0 and 7.3 km from the airport, average PNCs were 2 and 1.33-fold higher, respectively, when winds were from the direction of the airport compared to other directions, indicating that aviation impacts on PNC extend many kilometers downwind of Logan airport. Furthermore, PNCs were positively correlated with flight activity after taking meteorology, time of day and week, and traffic volume into account. This correlation was not found with other pollutants. Similarly, Hudda and Fruin [15] found that PNC was higher in areas under landing jet trajectories. Finally, they used a diffusion charging instrument to simulate alveolar lung deposition, and found a five-fold increase in deposited surface area concentration 2 to 3 km downwind from the airport, decreasing to two-fold 18 km downwind. Riley et al. [24] took extensive measurements in neighborhoods around Los Angeles International Airport and Hartsfield-Jackson International Airport in Atlanta. They found a 3 to 5-fold increase in PNCs in transects under landing approach pathways. Shirmohammadi et al. [28] also took measurements at Los Angeles International Airport (LAX) and found PNCs were four times greater adjacent to the airport than on nearby major freeways. Stacey [31] conducted a literature survey and concluded that the literature consistently reports PNCs close to airports are significantly higher than locations distant and upwind of airports, and that the particle size distribution is different from traditional road traffic, with more extremely fine particles. Results of a monitoring study of communities near Seattle-Tacoma International Airport was also recently released [36]. It also found higher levels of UFP near the airport. Furthermore, the impacted area was larger than at near roadway sites. The PM associated with aircraft landing activity was also smaller with lower black carbon concentrations than near-roadway samples.

3.2. $PM_{2.5}$ and PM_{10}

The majority of studies that address the criteria pollutant PM focus on $PM_{2.5}$ or smaller particles. The levels found in airport measurement studies vary, ranging from relatively low levels to those that are close to or exceeding the NAAQS. In addition, results are less consistent than for UFP.

At LAX in 2005–2006, Zhu et al. [47] observed that daily mean $PM_{2.5}$ concentrations collected up to 600 m from the take-off runway were significantly greater ($p < 0.001$) than at a background site. However, Shirmohammadi et al. [28] observed $PM_{2.5}$ concentrations were generally lower at LAX than inside freeways within the impact zone, although, as mentioned in the introduction, particle number concentrations were greater. At Santa Monica Municipal (SMO) mobile monitoring conducted by Choi et al. [6] in 2008 and 2011 showed comparable or lower concentrations in a residential neighborhood 120–480 m predominately downwind of SMO as compared to a neighborhood located in perpendicular wind to the airport. Similarly, Hudda et al. [12] observed that $PM_{2.5}$ concentrations were not elevated during impact-sector winds relative to non-impact-sector winds at a residence approximately 1.3 km from BOS. Higher $PM_{2.5}$ concentrations were observed from a wind direction that indicated long-range transport of aerosols from regional sources upwind. $PM_{2.5}$ was not correlated with flight activity, suggesting $PM_{2.5}$ was primarily from sources other than aircraft. Air quality modeling studies [25,43] indicate higher $PM_{2.5}$ concentrations near airports. In London, however, two measurement studies at Heathrow Airport showed similar or lower concentrations at the airport than in central London [22,50].

3.3. Black carbon

Studies indicate that black carbon (BC) is elevated in the vicinity of airports, as far away as 10 km. Westerdahl et al. [41] and Zhu et al. [47] observed elevated BC at take-off downwind of LAX. BC is emitted by a variety of combustion sources in addition to aircraft. Westerdahl et al. calculated a 12-fold increase in BC immediately downwind of the airport, although concentrations were comparable or lower than observed at nearby freeways. Zhu et al. [47] observed that BC decreased markedly with increasing distance from the runway because of atmospheric dispersion processes, however elevated levels were still observed at 600 m downwind as compared to background. Furthermore, at Logan Airport, Hudda et al. [12] observed that, in contrast to the $PM_{2.5}$ results discussed above, BC was 1.3-fold elevated during impact-sector winds than non-impact-sector winds at a residence sampled 1.3 km from the airport in 2017. Finally, at T.F. Green Airport, Dodson et al. [51] developed regression models which found that aircraft activity contributed 24–28% of the total BC based on measurements in 2005–2006 from five sites located 0.16–3.7 km from the airport. However, international studies have not shown a clear association ([22], [17], [23]).

3.4. Gaseous criteria pollutants

In general, most on-airport studies in the U. S. showed slightly elevated concentrations of gaseous criteria pollutants, specifically carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), even though concentrations are often still below national ambient air quality standards. Off-airport studies had more varied results, but some studies show aviation contributions up to 12 km from the airport. Moreover, nitrogen oxides are more likely to be elevated than sulfur or carbon oxides. Ground support equipment and motor vehicles also contribute to these pollutants, especially NO_2 (as well as NO). Among the studies that address these pollutants, Hudda et al. [12] observed at Logan airport that levels of oxides of nitrogen (NO, NO_2, and NO_x), and CO are significantly higher (1.1 to 1.9-fold elevations) in impact sector winds than non-impact sector winds. At up to 12 km from LAX, Hudda et al. [16] observed elevated nitrogen oxides, with similar NO_2 and particle number spatial patterns suggesting a common pollutant source. A number of other studies also showed elevated concentrations for one of more of these criteria pollutants [24], NO_2; [6], CO; [7], NO_2, CO, SO_2). However, study results were inconclusive for some pollutants [6], NO; [16], CO and SO_2; [1], NO_2; [19], CO_2 and NO_2. International studies also showed elevated levels of pollutants for many air pollutants [4,26,45,37,30,22].

3.5. Hazardous air pollutants

Very few studies assess hazardous air pollutants (HAPs), other than polycyclic aromatic hydrocarbons (PAHs). Past speciation work indicated formaldehyde and acetaldehyde make up a large percentage of total hydrocarbons from turbine engine aircraft (12 and 4 percent respectively) [34,35]; while earlier work characterized PAH emissions [52] .

At LAX in 2003, Westerdahl et al. [41] observed particle-phase polycyclic aromatic hydrocarbon (PM-PAH) concentrations two orders of magnitude higher at downwind location than upwind locations, although aircraft dominated areas showed lower PM-PAH than vehicular traffic areas. PM-PAH values observed at the site 500 m downwind of landings are only slightly elevated above the coastal background. In 2005, Zhu et al. [47] reported ambient air concentrations for both particulate phase and vapor phase PAHs collected from the blast fence and at a control site. A greater amount of PAH mass was in the vapor phase than in the particle phase. The levels of vapor-phase PAH were consistently higher at the LAX blast fence than at background site. For both sites, naphthalene comprised 80 to 85% of the total vapor-phase PAH mass. The semi-volatile PAHs (from phenanthrene to chrysene) were consistently higher at the LAX blast fence than the background site, whereas, the high molecular weight PAHs (from benzo[a] pyrene to indeno[1,2,3-cd]pyrene) were lower at the blast fence than the background site.

In a residential area near SMO in California in 2008, markedly elevated concentration peaks of particle bound PAH (PB-PAH) were observed up to 600 m downwind of SMO and 250 m perpendicular to the prevailing wind directions [6]. PB-PAH was associated with jet takeoffs but not with other aircraft operations such as idling, descents or takeoffs by reciprocal-engine aircrafts . During a freeway closure event near SMO in 2011, Choi et al. [6] observed highly elevated PB-PAH ambient air concentration which were likely explained by jet take-offs.

At a residential site 1.3 km from BOS, Hudda et al. [12] observed significantly higher PB-PAH concentrations in impact sector wind than non-impact-sector wind.

Substance	Health Effects	Daily intake (mg/day) or dose (mg/kg/day)	Public health impact/risk assessment
PM	0	0	0
UFP	4	0	0
PM2.5	1	0	0
PM2.5-10	0	0	0
Black Carbon	1	0	0
CO	1	0	1
NO2	2	0	0
NOx	0	0	0
O3	1	0	0
SO2	0	0	0
13-Butadiene	0	0	0
Acetaldehyde	0	0	0
Benzene	0	0	0
Naphthalene	0	0	0
Formaldehyde	0	0	1
Dioxins Furans	0	0	0
PAHs	1	0	0
Other	0	1	1

Fig. 4. Heatmap of studies by type of health data.

3.6. Health effects

This systematic review only identified a limited number of on-topic references with health effects, impact or risk data (Fig. 4). While this literature review was not intended to capture all relevant health effect studies, having focused on ambient air data, we summarize here the studies that were identified using our search parameters. Additionally, the systematic review focused on peer-reviewed articles from databases, rather than government or airport studies which may be more likely address public health issues. Potential endpoints identified in this literature review are as follows:

- Yim et al. [44] assessed global, regional and local health impacts of civil aviation emissions, using modeling tools that address environmental impacts at different spatial scales. The study attributed approximately 16,000 premature deaths per year globally to global aviation emissions, with 87% attributable to $PM_{2.5}$. The study concludes that about a third of these mortalities are attributable to $PM_{2.5}$ exposures within 20 km of an airport.
- Wing et al. [42] evaluated whether UFPs from jet aircraft emissions are associated with increased rates of pre-term birth among pregnant mothers living within 15 km downwind of LAX. The study, consisted of 147,186 mothers who gave birth between 2008 a and 2016. The study concludes that aircraft emissions play an etiologic role, independent of noise and traffic-related pollution. Specifically, the odds ratio (OR) per interquartile range (IQR) increase relative to UFP exposure was 1.04.
- Lammers et al. [21] investigated respiratory and cardiopulmonary outcomes in 21 healthy adults who were repeatedly exposed to ambient air in a mobile laboratory set up 300 m from the runway at Amsterdam Schipol Airport (2 to 5 visits, 5 h each). Total PNC was significantly associated with decreased lung function, primarily a decrease in forced vital capacity (FVC) and prolonged corrected QT (duration of ventricular repolarization corrected for heart rate). The authors observed small effects after only a single 5 hr exposure. These effects were mainly associated with particles < 20 nm.
- At LAX, Hudda and Fruin [15] measured alveolar lung deposited surface area (ALDSA), which is the fraction of lung deposited surface area (LDSA) deposited in the alveolar region of the lung. The particle number concentration increases in the areas impacted by LAX are accompanied by pronounced decreases in particle size and increases in ALDSA concentration.
- Using ambient $PM_{0.25}$ collected adjacent and downwind from LAX in 2016 as well as PM directly sampled from diluted exhaust of turbine and diesel engines, He et al. [9] demonstrated adverse responses in human bronchial epithelial (16HBE) cells, specifically effects on cell viability/cytotoxicity, ROS activity and inflammatory mediators release. The paper suggested that elemental composition and oxidative potential of the PM samples seem to explain these biological responses.
- Cavallo et al. [5] characterized the exposure to several polyaromatic hydrocarbons (PAHs) and evaluated the genotoxic and oxidative effects in airport personnel (n = 14) at Da Vinci airport in Rome, Italy. Air sample were collected at the airport apron, building, and terminal/office areas. Urine and blood samples were collected from exposed individuals (those that work in close proximity to the airport) and control individuals (those that work in the administrative offices of the airport). Genotoxic effects and early direct-oxidative DNA damage were evaluated by micronucleus and formamidopyrimidine DNA glycosylase (Fpg) modified comet assay [29] on lymphocytes and exfoliated buccal cells, and by chromosomal aberrations and sister chromatid exchange analyses. Urinary OH-pyrene did not show differences between exposed and controls, although the controls may have low daily exposure to PAH. The results found an induction of sister chromatid exchange due to PAH exposure and an increase of total chromosomal aberrations.
- Senkayi et al. [27] evaluated whether there is an association between childhood leukemia cases and airport emissions in Texas over a 10-year period. The work concluded that an association exists based on 1) comparison of distance to airports with incidence ratios in census blocks, and 2) regression model to predict childhood leukemia incidences based on benzene emissions from various sources.

Recently, a systematic review of health effects associated with exposure to jet engine emissions in the vicinity of airports was published [3]. This study concluded that literature on health effects was sparse but jet engine emissions have physicochemical properties similar to diesel exhaust particles, and that exposure to jet engine emissions is associated with similar adverse health effects as exposure to diesel exhaust particles and other traffic emissions.

3.7. Data strengths and limitations

The papers identified in these studies consistently showed UFP is elevated in and around airports. The most recent studies have heavily focused on UFP and addressed gradients with increasing distance from airports. Furthermore, most of the studies addressed contributions from background and freeways, and at least qualitatively characterized airport and aircraft data with respect to air quality.

However, a lack of standard methods and instrumentation make comparisons of measured concentrations among studies difficult. In addition, there are very few long-term studies. Finally, only a few airports have been studied, making it difficult to provide broad generalizations when differences in airport and aircraft operations, geography, and meteorology have a significant impact on the results.

3.8. Recommendations for future work

This literature review underscores the need for research in a number of key areas:

- Characterization of ambient particle size distribution from specific aircraft activities (i.e., take-off and landing). While research shows the near airport environment is a hotspot for $PM_{2.5}$ and UFP, particle size distributions may vary spatially within that environment depending on where different types of activity occur. This spatial distribution (i.e. take-off and landing) needs to be better characterized.
- Investigation of particle size distribution changes with increasing distance from the airport.
- Attribution of concentrations to individual source types. For example, roadway traffic emissions from nearby freeways may make a significant contribution to ambient concentrations in the vicinity of airports.
- Assessment of the relationship between UFP and other pollutants, especially HAPs.
- Improvement of the understanding of the health effects and impacts of pollutants and disparate impacts on minority or disadvantaged communities as well as children.
- Conducting long-term studies to capture variation in ambient concentrations across years and seasons.
- Conducting studies at more airports to capture differences in airport source types (e.g., aircraft fleet mixes), source operations, airport layout and location, surrounding geography, and meteorology.

Disclaimer

The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U. S. Environmental Protection Agency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cacint.2021.100066.

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