Model-extrapolated Estimates of Airborne Lead Concentrations at U.S. Airports

United States Environmental Protection Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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EPA United States Environmental Protection Agency

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Abbreviations

Air Quality (AQ)
Air Quality Factor (AQF)
Air Taxi (AT)
Air Traffic Activity Data System (ATADS)
Airport Cooperative Research Program (ACRP)
American Meteorological Society/Environmental Protection Regulatory Model (AERMOD)
Clean Air Act (CAA)
US Environmental Protection Agency (EPA)
US Federal Aviation Administration (FAA)
General Aviation (GA)
General Aviation and Air Taxi Activity Survey (GAATA)
Landing and take-off operations (LTOs)
Multi-Engine (ME)
National Ambient Air Quality Standard (NAAQS)
National Academies of Sciences (NAS)
National Emissions Inventory (NEI)
One hundred octane low lead (100LL)
Reid-Hillview Airport of Santa Clara County (RHV)
Santa Monica Municipal Airport (SMO)
Single-Engine (SE)
Terminal Area Forecast (TAF)
Tetraethyl lead (TEL)
Touch-and-Go (T&G)

Summary

The main objective of the analyses presented in this report is to estimate the potential ranges of lead concentrations at and downwind of the anticipated area of highest concentration at airports in the US. To accomplish this objective, the relationship between piston-engine aircraft activity and lead concentration at and downwind of the maximum impact site at one airport was applied to piston-engine aircraft activity estimates for each US airport. This approach for conducting a nationwide analysis of airports was selected due to the dominant impact of piston-engine aircraft run-up operations on ground-level lead concentrations, which creates a maximum impact area that is expected to be generally consistent across airports. Specifically, these aircraft consistently take-off into the wind and typically conduct run-up operations immediately adjacent to the take-off runway end, and thus, modeling lead concentrations from this source is constrained to variation in a few key parameters. These parameters include: 1) total amount of piston-engine aircraft activity, 2) the proportion of activity conducted at one runway end, 3) the proportion of activity conducted by multi-piston-engine aircraft, 4) the duration of run-up operations, 5) the concentration of lead in avgas, 6) wind speed at the model airport relative to the extrapolated airport, and 7) additional meteorological, dispersion model, or operational parameters. These parameters were evaluated through sensitivity analyses across airports or using quantitative or qualitative uncertainty analyses.

Results of the national analysis show that model-extrapolated 3-month average lead concentrations in the maximum impact area range from less than 0.0075 $\mu g/m^3$ up to 0.475 $\mu g/m^3$ at airports nationwide. The range of model-extrapolated concentrations in the maximum impact area aligns with expectations from previous monitoring at airports that showed exceedances of the lead NAAQS in the maximum impact area of some airports.[1] Results of the national analysis also demonstrate and quantify the gradient in lead concentrations with the highest concentrations in locations closer to the maximum impact area than those further downwind.

For the subset of airports where estimated lead concentrations could potentially be above the lead NAAQS, the analysis was further refined using a set of sensitivity analyses and airport-specific data. This airport-specific analysis identified some airports where model-extrapolated lead concentration estimates suggest the potential for piston-engine aircraft activity to cause lead concentrations above the lead NAAQS in the area of maximum impact with unrestricted public access. Lead concentration estimates in this analysis should not be used to evaluate attainment of the lead NAAQS.

Overall, comparisons of both national and airport-specific model-extrapolated concentrations to monitored values show general agreement and suggest that the extrapolation method

[1] For additional information on monitoring data collected at airports see: https://www.epa.gov/regulations-emissions-vehicles-and-engines/airport-lead-inventories-air-quality-monitoring-air.

presented in this report provides reasonable estimates of the range in concentrations of lead in air attributable to peak activity periods of piston-engine aircraft at airports. Uncertainty in the national and airport-specific activity analyses were evaluated using a Monte Carlo analysis, which characterized how variability in run-up duration and avgas lead concentrations influence model-extrapolated lead concentrations. Results showed that model-extrapolated lead concentrations may increase at airports with average run-up durations that are longer than the average run-up duration observed at the model airport, even if the avgas lead concentration is lower than that used in the national analysis. Additional, qualitative analyses were used to evaluate sources of uncertainty that were not addressed in sensitivity or Monte Carlo analyses.

Quantitative and qualitative evaluations of meteorological parameters that can impact model-extrapolated concentrations focused on adjusting concentrations to reflect site-specific wind speeds (See Section 3.2 for details) and evaluating changes in wind direction, mixing height, and temperature. While the wind speed adjustment did not meaningfully impact the range of concentrations in the maximum impact area of US airports, this adjustment does have an important impact on model-extrapolated concentrations at individual airports, particularly at those airports where wind speeds during the maximum activity period differ significantly from those observed at the model airport. As discussed in Section 4.4.1, minimal uncertainty is expected in model-extrapolated concentrations due to shifts in wind direction given that most airports are built with the predominate runway facing into the wind. It is also anticipated that mixing height has a minimal impact on uncertainty in model-extrapolated concentrations at the maximum impact area, because of the dominant impact of the very localized run-up emissions at this location and the fact that GA and AT aircraft activity occurs almost entirely during the day when vertical mixing is greatest. At downwind locations, mixing height may play a larger role and would be an important variable to examine when evaluating individual airports, particularly those with mixing height characteristics significantly different from the model airport. Finally, ambient temperature and other microclimate or meteorological variables are not expected to meaningfully impact nationwide results, however, there is more uncertainty in model-extrapolated concentrations at airports that have maximum activity periods during meteorological conditions not observed at the model airport.

Additional sources of potential uncertainty that were evaluated qualitatively included dispersion modeling inputs and operational parameters. While dispersion modeling inputs such as surface roughness, Bowen Ration, and albedo may result in some uncertainty at downwind locations, their impact on variability near the maximum impact site is mitigated due to consistency in on-airport characteristics and land-use requirements immediately downwind of runways based on landing and take-off safety requirements. As with meteorological parameters, the appropriateness of dispersion modeling inputs used in this analysis for individual airports with meaningful differences in land use of the areas immediately surrounding a runway would need to be considered on a case-by-case basis. Differences in operational parameters (e.g., piston/turboprop split and single-engine/multi-engine split, distribution of aircraft engine types operating at the airport, diurnal activity patterns) are not expected to contribute significantly to uncertainty in extrapolated concentration estimates for airports nationwide; however, in modeling individual airports, national fleet and operational data should be supplemented with local data where available and feasible.

The model-extrapolated lead concentrations provided in this report reflect only lead concentrations in air attributable to piston-engine aircraft activity and only at the area of maximum concentration and downwind of that location. Additional analyses, which are outside of the scope set by the objective of this report, would be necessary to evaluate concentrations of lead in air at other areas at and near airports. In addition, to understand total lead concentrations in air, other airborne sources of lead (e.g., nearby industrial sources, sources contributing to local background concentrations) would need to be considered. Understanding total lead exposure, which is relevant for understanding blood lead levels, would also need to consider exposure to lead from additional media (e.g., soil, drinking water).

1. Introduction

The United States (US) Environmental Protection Agency (EPA) is evaluating the air quality impact of emissions of lead from piston-engine aircraft operating on leaded fuel. One component of the evaluation includes conducting an analysis of concentrations of lead in air at and downwind of airports. This analysis was conducted to provide an understanding of the potential range in lead concentrations in air at the approximately 13,000 airports with piston-engine aircraft activity in the US. This report describes the methods that the EPA used to estimate these lead concentrations and presents the results of this analysis along with a quantitative uncertainty analysis. Background information is presented immediately below in order to provide a general understanding of the use of leaded fuel in aircraft, and the state of the science on modeling concentrations of lead in air from aircraft emissions at individual airports. Subsequent sections provide details on the analysis approach for airports nationwide.

1.1 Use of Leaded Avgas in Piston-Engine Aircraft

Emissions of lead from aircraft operating on leaded aviation gasoline (avgas) are the largest source of lead released into the atmosphere in the US, accounting for 62% of lead (456 tons) in the 2014 National Emissions Inventory (NEI) (USEPA 2016a). Leaded avgas is used in piston-engine aircraft, of which there are approximately 140,000 in the US (FAA 2014) . These aircraft operate at most of the approximately 20,000 US airport facilities (approximately 13,000 of which are airports, while the remainder are heliports, balloon ports, and other facility types) (FAA 2017).[2,3] Piston-engine aircraft conduct approximately 32 million landing and take-off operations (LTOs) annually (USEPA 2011).[4] Most piston-engine aircraft operations fall into the categories of either General Aviation (GA) or Air Taxi (AT) activity. GA is defined as the operation of civilian aircraft for purposes other than commercial, such as passenger or freight transport, including personal, business and instructional flying; AT is scheduled or on-demand services that carry limited payload and/or passengers (FAA 2012).

Piston-engine aircraft rely on lead as an additive to avgas to help boost fuel octane and prevent engine knock, as well as prevent valve seat recession and subsequent loss of compression for

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[2] This report focuses on fixed-wing piston-engine airplane activity at airports. Facility types other than airports are not included in this report; seaports and water runways at airports are both excluded from analyses in this report, and rotorcraft operations at airports are not included in this report. Appendix B provides some information on conducting additional rotorcraft analyses in the future.

[3] Data on airport facilities was downloaded from FAA Air Traffic Activity Data System (ATADS) at http://aspm.faa.gov/opsnet/sys/Airport.asp on 13 February 2014.

[4] Piston-engine aircraft conduct two types of operational cycles, or cycle-types. These cycle-types include: 1) a full landing-and-take-off operation (full LTO) during which the pilot conducts all pre-flight engine checks and completes full take-off and landing operations, and 2) a touch-and-go operation (T&G) during which the pilot briefly touches down on a runway before taking-off again almost immediately in order to practice take-off and landing procedures. This is a training exercise most commonly performed by student pilots. Throughout this report, “cycle-type” is used to refer to the full LTO and T&G categories, while “LTOs” is used to refer more generally to all cycle-types (i.e., both full LTO and T&G).

engines without hardened valves.[5] Lead is added to the fuel in the form of tetraethyl lead (TEL) along with ethylene dibromide, which acts as a lead scavenger to prevent lead deposits on valves and spark plugs. Currently one hundred octane low lead (100LL), which contains up to 2.12 grams of lead per gallon, is the most commonly used type of avgas in the US, although FAA survey data reports limited use of a leaded avgas containing 4.24 grams of lead per gallon, known as "100 Octane," and unleaded avgas (FAA 2015). Lead is not added to jet fuel, which is used in commercial aircraft, most military aircraft, and other turbine-engine aircraft.

1.2 Lead Concentrations in Air from Leaded Avgas Use in Piston-Engine Aircraft at Individual Airports

Lead emissions from piston-engine aircraft operating on leaded avgas increase concentrations of lead in air at and downwind of airports (Environment Canada 2000, Fine et al. 2010, Carr et al. 2011, Anchorage DHHS 2012, Feinberg et al. 2016). Gradient studies evaluating lead concentrations near airports where piston-engine aircraft operate indicate that concentrations of lead in air are one to two orders of magnitude higher at locations proximate to aircraft emissions compared to locations approximately 500- to 1000-meters downwind (Fine et al. 2010, USEPA 2010a, Carr et al. 2011, Feinberg et al. 2016). The most significant emissions in terms of ground-based activity, and therefore ground-level concentrations of lead in air, occur near the areas with greatest fuel consumption where the aircraft are stationary for a period of time (USEPA 2010a, Carr et al. 2011, ICF 2014, Feinberg et al. 2016). For piston-engine aircraft these areas are most commonly locations in which pilots conduct engine tests during run-up operations prior to take-off (i.e., magneto checks during the run-up operation mode). Run-up operations are typically conducted adjacent to the runway end from which aircraft take-off and the brakes are engaged so the aircraft is stationary.[6] As a result of the aircraft being stationary, duration of run-up, and high fuel consumption rate, emissions from run-up activity are the largest contributor to local maximum atmospheric lead concentrations; run-up emissions are estimated to contribute over 80% of the lead concentrations at and immediately downwind of the area where the run-up mode of operation occurs, even though this mode of operation does not have the highest fuel consumption rate (Appendix A). Hence, the area adjacent to the runway end at which run-up operations most frequently occur is identified here as the maximum impact site for lead concentrations.[7,8]

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[5] Minimum octane requirements as well as other carefully controlled fuel parameters in avgas prevent the general use of unleaded motor vehicle fuel in piston-engine aircraft.

[6] A single "runway" has a magnetic heading designation for each "runway end" in order to distinguish which direction the aircraft is taking off from or landing on to; we use "runway end" throughout this report.

[7] For purposes of this report and the underlying analysis, the maximum impact site is defined as 15 meters downwind of the tailpipe of an aircraft conducting run-up operations in the area designated for these operations at a runway end. The maximum impact area is the approximately 50 meters surrounding the maximum impact site. The downwind gradient is the approximately 500-meter area that extends from the maximum impact site. Additional characterization of the maximum impact site, area, and downwind gradient is provided in Section 2.

[8] While run-up operations are most frequently the location of the maximum impact site of aircraft lead emissions at airports, at some airports other operations such as taxi or idling near the runway may result in a hotspot of emissions. This report focuses on run-up as the location of the maximum impact site in an effort to characterize concentrations of lead in air at the location of maximum impact for most US airports. Additional analyses would be necessary to more specifically characterize concentrations of lead in air at individual airports.

1.3 Characterizing Maximum Impact Area Lead Concentrations from Piston-Engine Activity at U.S. Airports

The understanding of piston-engine aircraft lead emissions and resulting concentrations in air was developed through detailed monitoring and modeling studies at individual airports. However, conducting detailed air quality monitoring or modeling for lead at each of the 13,000 US airports is not feasible; thus, the analysis of concentrations of lead in air at and downwind of airports nationwide is based on detailed air quality modeling at a representative, model airport. The modeling results were used to develop factors that relate piston-engine aircraft activity to concentrations of lead in air. The factors, termed Air Quality Factors (AQFs), were used in conjunction with estimates of piston-engine aircraft activity at airports nationwide to calculate model-extrapolated concentrations at and downwind of each US airport.

The rationale for this approach is based on the consistent set of parameters required for the safe operation of a piston-engine aircraft. Specifically, piston-engine aircraft consistently conduct run-up operations prior to take-off, and the run-up activity has the following characteristics: 1) run-up operations require high fuel consumption rates while the aircraft is stationary, and thus are the location of the maximum impact site for lead concentrations, 2) the location of run-up activity occurs in a designated area proximate to the runway end from which aircraft take-off, and 3) the runway end used for take-off, and hence the location of run-up operations, can be identified using wind direction since piston-engine aircraft takeoff into the wind.

This analysis focuses on the maximum impact areas at airports nationwide (i.e., the 50 meters surrounding the maximum impact site adjacent to run-up operations). Notably, the maximum impact area lead concentration estimates provided in this report are based on average values for several key input variables; thus, the concentrations are not "worst-case" estimates (i.e., they do not reflect the use of the maximum values for all the key input parameters). For each US airport, model-extrapolated lead concentrations are calculated as 3-month average values to maintain consistency with the form of the National Ambient Air Quality Standard (NAAQS) for lead (i.e., a maximum 3-month average of 0.15 $\mu g/m^3$) (National primary and secondary ambient air quality standards for lead 40 CFR 50.12, USEPA 2016b). Importantly, while model-extrapolated concentrations are calculated and presented in a manner consistent with the lead NAAQS, these results should not be used to determine attainment of the lead NAAQS at individual airports. Information on the process that EPA, the states, and the tribes follow to determine whether or not an area is meeting the NAAQS for lead is described on the EPA website (USEPA). Lead concentration estimates presented in this report are provided to inform an understanding of the potential range of impacts that lead emissions from piston-engine aircraft alone may have on air quality in close proximity to this source of lead. Due to the inherent uncertainties in extrapolating relationships between concentration and activity from one well-characterized model airport to others, uncertainty and variability in model-extrapolated lead concentrations is characterized.

This document is organized to first provide the methods and results of detailed air quality modeling of lead at a model airport (Section 2). Section 3 describes how the modeling results were used to develop a quantitative relationship between piston-engine aircraft activity and lead concentrations; this section further provides the methodology to estimate piston-engine aircraft activity at airports nationwide, which is used to calculate lead concentrations at airports nationwide based on the relationship between activity and lead concentrations. Section 3 also presents methods to identify a subset of airports for more in-depth analyses using airport-specific data. Section 4 presents the model-extrapolated lead concentrations that result from combining piston-engine aircraft activity estimates with the relationship between activity and lead concentrations in the maximum impact area and locations downwind at each airport nationwide. In addition, Section 4 characterizes uncertainty and variability in these model-extrapolated lead concentrations.

2. Air Quality Modeling of Lead from Piston-Engine Aircraft at a Model Airport

To characterize concentrations of lead in air at and downwind of the maximum impact area of airports nationwide, EPA first conducted detailed air quality modeling at a model airport. The results of this detailed air quality modeling were used to develop factors, known as AQFs, which provide quantitative relationships between piston-engine aircraft activity and lead concentrations at and downwind of the maximum impact site at the modeled airport. The AQFs were subsequently applied to estimates of aircraft activity at other airports across the country in order to calculate model-extrapolated lead concentrations at and downwind of the maximum impact area of airports nationwide. In this section we briefly explain the overall approach for the detailed air quality modeling at the model facility, summarize the model performance, and then discuss how the air quality modeling was conducted to develop the AQFs.

2.1 Overview of Air Quality Modeling at a Model Airport

In order to characterize local-scale air quality impacts of lead at a model airport, EPA applied the air quality model that is used for EPA and Federal Aviation Administration (FAA) regulatory analysis of near-field gradients of primary pollutants such as lead, namely the American Meteorological Society (AMS)/EPA Regulatory Model (AERMOD).[9,10] Since AERMOD had not been previously applied to modeling lead emissions from piston-engine aircraft activity, EPA developed the necessary model inputs and parameters, including: piston-engine aircraft parameters (i.e., sub-daily time-in-mode activity, dispersion due to aircraft turbulent wake, allocation of approach and climb-out emissions at altitude) and emissions characteristics of non-aircraft sources (e.g., nearby roads) (USEPA 2010a, Carr et al. 2011). These model inputs were developed and first applied at a GA airport (Santa Monica Airport, SMO) that was selected due to the availability of previously collected lead monitoring data, which indicated elevated concentrations of lead in air at and near the runway (Fine et al. 2010). Additional monitoring data were collected in parallel to the development of AERMOD modeling inputs in order to evaluate model performance. Details regarding the AERMOD inputs, model performance, and results are published elsewhere (USEPA 2010a, Carr et al. 2011).

The foundational work to establish AERMOD inputs for modeling lead emissions from piston-engine aircraft at SMO provided an understanding of the key characteristics of the relationship between aircraft activity and concentrations of lead in air. Some of the key findings from this work, included: 1) piston-engine aircraft operations increase ground-level concentrations of lead, with the largest concentrations resulting from engine checks prior to take-off (i.e., run-up operations), 2) lead concentrations attributable to piston-engine aircraft decrease with

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[9] AERMOD is a steady-state plume model that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain. Additional details about AERMOD are available at: https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models

[10] The FAA inventory tool for air emissions and noise, Aviation Environmental Design Tool (AEDT), does not include lead emissions (https://aedt.faa.gov/Documents/AEDT_2b_NEPA_Guidance.pdf).

increasing distance from the run-up location, such that the maximum impact location is immediately adjacent to the run-up area at a runway end, and 3) above-background lead concentrations occur up to 900 and 450 meters downwind of the maximum impact location on a daily and average 3-month basis, respectively (USEPA 2010a, Carr et al. 2011). The National Academies of Sciences (NAS) Airport Cooperative Research Program (ACRP) subsequently conducted a similar study of airport lead concentrations at three airports and similarly identified run-up as a critical operation mode to evaluate when modeling the impact of piston-engine aircraft lead emissions on ground-based lead concentrations (Heiken et al. 2014, Feinberg et al. 2016). These findings presented a clear approach for conducting air quality modeling at an airport, which would be used as a model facility for developing AQFs and subsequently characterizing concentrations of lead in air at and downwind of airports nationwide.

Reid-Hillview Airport of Santa Clara County (RHV) was selected as a representative GA airport for use as the model airport.[11] To apply AERMOD at the model airport, aircraft and meteorological data, similar to those collected at SMO, were collected at RHV. Specifically, data collected at this facility included: 1) number and type of piston-engine aircraft LTOs, 2) time in each operating mode, 3) time-of-day and day-of-week patterns of aircraft activity, 4) the concentration of lead in avgas, and 5) meteorological data (i.e., wind direction, wind speed, mixing height, temperature). These inputs were collected first for a seven-day period in order to characterize model performance at the model airport through comparisons of modeled and monitored concentrations. After characterizing model performance, additional activity and meteorology data were collected to model a yearlong period, which was then used to develop AQFs. Information on model performance at the model facility is presented immediately below in Section 2.2; information on the yearlong modeling is in Section 2.3. Appendix A provides details on specific AERMOD inputs at the model airport study, as well as information regarding the piston-engine aircraft modeled at the model airport compared to the national piston-engine aircraft fleet.

2.2 Air Quality Model Performance at a Model Airport

Comparisons of modeled and monitored daily average concentrations at the model airport were conducted over a seven-day period at three monitoring sites (upwind, 60 meters downwind, and at the maximum impact site). The daily average was over 15 hours, from the hours of 7 a.m. to 10 p.m. local time, representing the time when the airport was operational. The overall R^2 value across the three monitoring sites regressed against the paired modeled concentrations was 0.83, as shown in Figure 1. At the maximum impact site, the model tended to under-predict monitored concentrations for the seven days of comparison conducted, but was generally within 20% of monitored values and was within the 2:1 and 1:2 lines for all but

[11] RHV is considered generally representative of GA airports based on several factors, including: type of piston-engine aircraft operations, runway configuration, fleet composition of piston-driven aircraft engine technology types, and diurnal profile of piston-engine aircraft activity (see Appendices A and B for comparisons of RHV fleet and diurnal profiles relative to other GA airports).

one monitored value.[12] The generally good agreement between modeled and monitored concentrations was also observed in previous studies comparing AERMOD air quality dispersion model output with on-site monitoring data for lead at airports (Carr et al. 2011; Feinberg et al. 2016). As observed in these other studies, modeled lead concentrations can be both slightly over- and underestimates of on-site monitored values, and the performance observed for the model airport is considered to be aligned with prior work. We focused on understanding discrepancy between modeled and monitored concentrations on the few days when the discrepancy was greater than 20%. For these days, sensitivity analyses were conducted to identify possible reasons for the divergence. Details on the sensitivity analyses are presented in Appendix A, but generally showed that run-up location, run-up duration, and relative levels of multi-engine aircraft activity explained instances when the model under- or over-predicted monitored concentrations; uncertainty and variability in monitored values are not evaluated here, but also contribute to the divergence in these comparisons with modeled data. In addition, variability in emission rates for a given engine and across engine types will also contribute to variability in measured concentrations, as discussed in Section 4.4. The application of a 3-month averaging time is expected to minimize the impact of individual days in which the model may have over- or under-predicted lead concentrations. Comparisons between model-extrapolated concentrations, based on the AQFs developed at the model airport, and monitored concentrations at airports other than the model airport are presented in Section 4.

[12] Agreement with monitored concentrations within a factor of two is a common model evaluation criterion Chang, J. and S. Hanna (2004). Air quality model performance evaluation. *Meteorology and Atmospheric Physics,* 87 (1), 167-196, Luecken, D., W. Hutzell and G. Gipson (2006). Development and analysis of air quality modeling simulations for hazardous air pollutants. *Atmospheric Environment,* 40 (26), 5087-5096.

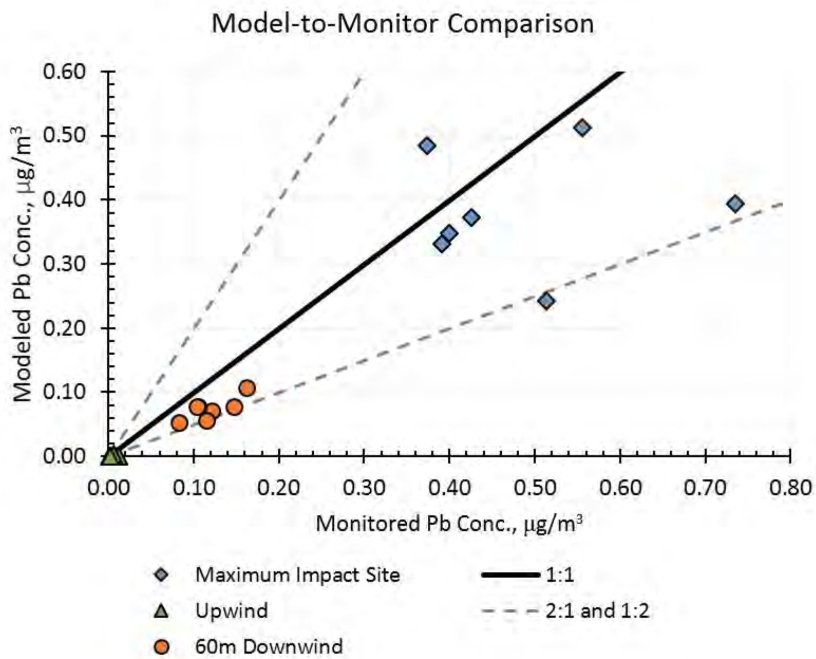

Figure 1. Comparison of modeled and monitored daily average concentrations at three sites at the model airport during a 7-day period.

The model performance at the model airport confirmed previous work showing that a limited set of parameters influence concentration in the maximum impact site, and supported moving forward with the development of AQFs to characterize the relationship between piston-engine aircraft activity and lead concentrations at and downwind of a maximum impact area.

2.3 Yearlong Air Quality Modeling to Develop AQFs at a Model Airport

This section provides general information used to model yearlong concentrations of lead in air that were subsequently used to calculate 3-month average AQFs at the model facility. Details regarding inputs to AERMOD including aircraft emission inventories, source parameterization, meteorological inputs, and receptor placement are provided in Appendix A.

As noted above, air quality modeling for this work built on prior piston-engine aircraft modeling in which aircraft- and airport-specific parameterizations were used in AERMOD to evaluate near-field gradients in ambient lead concentrations. Inputs in the yearlong modeling included 1) a detailed inventory for emissions of lead from piston-engine aircraft (i.e., aircraft activity, source locations, and lead emission rates), 2) meteorological data, 3) a dense receptor grid, and 4) piston-engine aircraft characterization and parameterization. Using previously published modeling methods, which are further described in Appendix A, Section 1.5, aircraft lead emissions were modeled as volume sources. The parameterization of aircraft lead emissions at the model airport included aircraft wake turbulence, and plume rise from ground-based aircraft emissions. Specific values for the initial vertical and horizontal dispersion by operation mode are provided in Appendix A.

Aircraft activity data for the yearlong modeling at the model facility used on-site observations in conjunction with on-site daily operations data collected by FAA. [13] Hourly aircraft activity profiles were developed from on-site observations for single-engine and multi-engine aircraft conducting either full landing and take-off or touch-and-go operation cycles. Time spent in each mode (i.e., start-up, idle, taxi, run-up, take-off and landing) was recorded during the days of observation and was used along with fuel consumption rates by mode to calculate emissions by mode. Source locations for all modes of aircraft activity (i.e., start-up, idle, taxi, run-up, take-off and landing) are described in Appendix A; emissions at altitude were represented using volume sources at 50-meter intervals up to approximately 500 meters and release heights for ground-based activity were 0.5 meters.

Surface and upper-air meteorological data (from stations 10 km, and 55 km away from the model facility, respectively) were processed using AERMOD's meteorological preprocessor, AERMET, to produce hourly data on mixing heights, stability, wind direction, wind speed, temperature, and precipitation. The wind direction data were used to identify the runway end from which piston-engine aircraft took off during each hour of each day in the year of modeling (2010). Surface characteristics and AERSURFACE parameterization are described in the Appendix A.

To identify the spatial extent of elevated lead concentrations within the vicinity of the airport, 2,250 receptor locations were used, with the most densely located receptors placed at 50-meter intervals at and near ground-based aircraft activity, as well as out to 1 km downwind from run-up and take-off activity. Receptor spacing was at 100-meter intervals at other locations within the 1 km perimeter of the runway centroid, and increased to 200 meters after 2 km.

Results of the yearlong model run provided daily lead concentrations at and downwind of the maximum impact site that are attributable to piston-engine aircraft activity (i.e., do not include background lead concentrations from other sources). These daily average lead concentrations were used to calculate 3-month, rolling-average lead concentrations. As detailed in Section 3 below, the 3-month, rolling average lead concentrations were then used to calculate AQFs that relate piston-engine aircraft activity over 3-month periods to lead concentrations at and downwind of the maximum impact site. The combination of the AQFs and activity estimates at other US airports provides model-extrapolated lead concentrations for a national analysis of lead concentrations at and downwind of maximum impact areas at airports nationwide.[14]

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[13] As discussed in Section 3, FAA data does not indicate which aircraft operations are conducted by piston-engine aircraft, compared to turboprop or other engine types. Rather activity is reported as specific to GA or AT, which can be used to estimate activity specific to piston-engine aircraft based on national averages or airport-specific data. For the model airport, data collected at the airport during the model-to-monitor comparison evaluation provided inputs to appropriately allocate GA and AT aircraft activity to piston-engine activity. For additional information see Appendix A.

[14] As stated in Section 1 we define maximum impact site as the 15 meters immediately adjacent to run-up and the maximum impact area as the 50 meters surrounding the maximum impact site. 'Maximum impact site' is used in

3. Method to Calculate Model-Extrapolated Lead Concentrations Nationwide

In this section we discuss the methods for calculating model-extrapolated lead concentrations at US airports. Section 3.1 provides the AQFs developed from the yearlong air quality modeling at the model airport discussed above. Section 3.2 provides the methodology for estimating activity at each airport and shows how we use activity estimates for each airport in combination with the AQFs to develop a national analysis of model-extrapolated concentrations of lead attributable to piston-engine aircraft at and downwind of the maximum impact area at approximately 13,000 US airports. This national analysis uses US average statistics for the fraction of GA and AT activity conducted by piston-engine aircraft. This analysis is further refined using airport-specific data for a subset of airports as described in Section 3.3. Section 3.4 then describes quantitative Monte Carlo uncertainty analyses for both the national and airport-specific analyses.

3.1 Calculation of AQFs for Piston-Engine Aircraft Activity and Lead Concentrations

The AQFs were calculated for the different piston-engine aircraft cycle types and engine classes. Specifically, piston-engine GA and AT aircraft perform two types of operational cycles: 1) full LTOs, in which aircraft start or end the operation in a full stop outside of the active runway, and 2) T&Gs, in which aircraft land and take-off without coming to a full stop.[15] Further, fixed-wing piston-engine GA and AT aircraft can be subdivided into two classes, single-engine (SE) and multi-engine (ME) planes. Due to differences in fuel consumption and time in each operational mode between aircraft classes and cycle-types, respectively, an AQF was calculated specific to each aircraft class (i.e., single- or multi-engine, SE or ME) and cycle-type (i.e., full LTO or T&G). Accordingly, four different types of AQFs (i.e., SE full LTO, SE T&G, ME full LTO, ME T&G) were calculated for nine specific receptor sites at and downwind of the maximum impact site, which was the runway end at which LTOs most frequently occurred at the model airport facility. The AQFs are calculated as the ratio of the average lead concentration over rolling 3-month time periods to piston-engine aircraft LTOs at the most frequently used runway end over the same 3-month period.[16] For example, the SE full LTO AQF at the maximum impact site is the ratio of the 3-month average modeled lead concentration (μg/m^3) attributed to SE LTO at the model airport maximum impact site and the number of full LTOs conducted by SE piston aircraft at the most frequently used runway end in the same 3-month period (Equation 1).[17]

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the context of the model airport and 'maximum impact area' is used in the context of airports for which we calculated model-extrapolated lead concentrations.

[15] As noted in Footnote 3, for simplicity, both types of LTOs (i.e., full LTO and T&G) are referred to as LTOs, while "cycle-type" is used to denote the categories of full LTO and T&G.

[16] As noted in Section 1, this analysis uses 3-month average lead concentrations to allow for comparisons with the 3-month average concentration set for the lead NAAQS USEPA (2016b). Review of the National Ambient Air Quality Standards for Lead **EPA–HQ–OAR–2010–0108; FRL–9952–87–OAR**.

[17] Both full LTO and T&G AQFs include concentration attributable to emissions from aircraft operating in all modes (e.g., taxi, take-off, run-up), with the exception that T&G AQFs do not include the lead concentration due run-up emissions.

$$\text{Eq. 1: SE full LTO AQF at maximum impact site} = \frac{\text{3-month average modeled lead concentration} \left(\frac{\mu g}{m^3}\right)}{\text{\# of full SE LTOs during 3-month period}}$$

The specific steps to calculate AQFs at and downwind of the maximum impact site are:

1. Calculate average modeled daily lead concentrations at each of the nine receptor locations over fourteen consecutive one-month periods separately for emissions from each aircraft class and cycle-type (e.g., SE T&G, ME full LTO).
2. Calculate rolling 3-month average modeled lead concentrations at each of the nine receptor locations by averaging across monthly average concentrations attributable to each aircraft class and cycle-type (e.g., SE T&G, ME full LTO).
3. Sum piston-engine activity by cycle-type and aircraft class (e.g., SE T&G, ME full LTO) in the 3-month periods.
4. Divide each 3-month average ambient lead concentration at each receptor site for each cycle-type and aircraft class by the corresponding total number of LTOs separated by cycle-type and aircraft class (e.g., ambient lead concentration from SE full LTO emissions at 50 m during July – Sept. 2011 / # of SE full LTOs during July – Sept. 2011).
5. Calculate the average AQF across the 12 rolling 3-month periods separately for each aircraft class and operation-type pair at each of the nine receptor locations (e.g., average of the 12, 3-month AQFs for SE full LTOs at the 50-meter receptor site).

As Steps 1 through 4 above describe, for each aircraft class and operation-type pair 12 AQFs were calculated for each set of 3 consecutive months in a 14-month period. The set of 12 AQFs for each aircraft class and operation type were used to evaluate variability in AQFs due to changes in meteorology over a 14-month period.[18] In order to average across the largest range in meteorology inputs to AQFs (e.g., wind speed), the resulting 12 AQFs were averaged to provide a single 3-month AQF for each aircraft class, operation-type, and location combination (Table 1). The extent to which meteorology variability included in the modeling to calculate AQFs is representative of the range of meteorology at airports across the country is discussed further in Section 4.

[18] Variation in the rolling 3-month average AQFs for full LTOs is generally +/-25% of the mean across all 12 AQFs. Specifically, rolling 3-month average AQFs for SE full LTOs vary from 28% greater to 14% less than the associated mean AQFs. For ME full LTOs, the individual rolling 3-month AQFs vary from 23% greater to 13% less than the associated mean AQFs. The variation is consistent across locations. While ME aircraft typically have two engines, ME AQFs are more than double the equivalent SE AQFS due to greater fuel consumption of their engines and differences in time-in-modes. The T&G AQFs are one to two orders of magnitude smaller than the full LTO AQFs in the same location, and variability between AQFs is somewhat larger by percentage (46% greater to 16% less than the associated mean AQFs) but smaller in absolute terms.

Table 1. Average of the 12 rolling 3-month AQFs (µg Pb/m³/LTO) at and downwind of the maximum impact site [19]

AQFs	Distance (meters)								
	Max Impact Site	50 m	100 m	150 m	200 m	250 m	300 m	400 m	500 m
SE Full LTO	$1.5x10^{-5}$	$3.5x10^{-6}$	$1.6x10^{-6}$	$1.1x10^{-6}$	$9.2x10^{-7}$	$7.6x10^{-7}$	$5.5x10^{-7}$	$4.0x10^{-7}$	$2.9x10^{-7}$
SE T&G	$1.7x10^{-7}$	$1.6x10^{-7}$	$1.7x10^{-7}$	$1.3x10^{-7}$	$1.2x10^{-7}$	$1.0x10^{-7}$	$8.0x10^{-8}$	$6.1x10^{-8}$	$5.5x10^{-8}$
ME Full	$9.0x10^{-5}$	$2.3x10^{-5}$	$1.1x10^{-5}$	$8.2x10^{-6}$	$6.6x10^{-6}$	$5.5x10^{-6}$	$4.0x10^{-6}$	$3.0x10^{-6}$	$2.2x10^{-6}$
ME T&G	$6.8x10^{-7}$	$5.0x10^{-7}$	$4.5x10^{-7}$	$3.3x10^{-7}$	$2.7x10^{-7}$	$2.2x10^{-7}$	$1.7x10^{-7}$	$1.3x10^{-7}$	$1.2x10^{-7}$

When each AQF is multiplied by the number of corresponding LTOs (full LTOs or T&Gs) that occur at the most frequently used runway end during a 3-month period, the sum of the products equals the lead concentration over the 3-month period at each of the nine locations. The concentration of lead in air, $[Pb]_{Air}$, is calculated by Equation 2, where Avgas[Pb] is the concentration of lead in fuel and PA is piston activity for the given engine and operation type. The next section describes how the number of piston-engine LTOs, specific to aircraft class and operation-types, was estimated for each US airport in order to calculate 3-month average model-extrapolated concentrations of lead in air at each airport.

Eq. 2[20,21]:

$$[Pb]_{Air}=$$

$$\frac{\text{Avgas[Pb]}\,\frac{\text{g Pb}}{\text{gal}}}{2.12\,\frac{\text{g Pb}}{\text{gal}}}\left[\left(PA_{SE,Full}\times AQF_{SE,\ Full}\right)+\left(PA_{SE,\ T\&G}\times AQF_{SE,\ T\&G}\right)+\left(PA_{ME,\ Full}\times AQF_{ME,\ Full}\right)+\left(PA_{ME,\ T\&G}\times AQF_{ME,\ T\&G}\right)\right]$$

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[19] Additional information on the relationships between AQFs and distances downwind is available in Appendix C.

[20] Per the description in the above text, the concentration of lead in air is calculated at nine distances starting immediately adjacent to run-up out to 500 meters downwind.

[21] The scalar for the concentration of lead in avgas is used to normalize the lead concentration to the ASTM specification for 100 LL (ASTM International (2016). *Standard Specification for Leaded Aviation Gasolines*. https://compass.astm.org/EDIT/html_annot.cgi?D910+19). The impact of variability in avgas lead concentrations on model-extrapolated lead concentrations is discussed in Section 3.4.

3.2 National Analysis Methods

This section summarizes the approach and rationale for the national analysis of lead concentrations at and downwind of the maximum impact area at US airports. At a high-level, this approach entails estimating piston-engine aircraft activity at each runway end of each airport, and then combining activity estimates from the most actively used runway end in a 3-month period with the AQFs presented in the previous section. The following text describes, in brief, the methods used to estimate 3-month maximum piston-engine aircraft activity at each runway end for airports nationwide; the detailed methods for this analysis are provided in Table 2.

Airport-specific piston-engine aircraft activity data are not collected by FAA or reported by airports in a national data source. Rather, piston-engine aircraft activity is reported by FAA as part of GA and AT activity, which can also include jet-engine aircraft activity. To estimate piston-engine activity, we used national datasets as described in Appendix B and FAA survey data regarding the national average for number of hours flown by piston-engine GA or AT aircraft nationwide.[22] Specifically, the percent of hours flown by piston-engine aircraft categorized as GA (72%) and, separately, AT (23%) was used to estimate the number of LTOs conducted by piston-engine aircraft at US airports that report GA and AT LTOs (e.g., if an airport reports 100 GA LTOs and 10 AT LTOs, then 72 and 2 LTOs would be attributed to piston-engine aircraft for each respective category). For airports that do not report LTOs conducted by GA and AT, EPA expanded on an FAA method to estimate LTOs using data on the number of aircraft based at the airport (i.e., aircraft that are air worthy and operational that are based at an airport for the majority of the year, commonly referred to as "based aircraft").[23] This approach to estimate piston-engine LTOs is routinely applied in the EPA National Emissions Inventory and is documented in full on the EPA website.[24] The national analysis of lead concentrations at and downwind of airports nationwide used these annual piston-engine LTO estimates to calculate the number of piston-engine LTOs at each runway end of US airports over 3-month rolling periods as described below (Figure 2).[25] For this analysis, annual piston-engine LTO estimates

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[22] Data on hours flown by piston-engine aircraft is consistent with activity data (LTOs), but activity data are reported as number of LTOs conducted by piston-engine aircraft in both GA and AT categories, whereas hours flown data are reported for piston-engine aircraft in GA and, separately, AT categories. Piston-engine aircraft flew 65.8% of hours categorized as GA and AT combined compared to conducting 65.7% of LTOs categorized as GA and AT combined. Piston-engine aircraft flew 72% of hours categorized as GA, and, separately, 23% of those categorized as AT.

[23] When airports do not report LTOs specific to GA and AT activity, then the number of aircraft that can use leaded fuel (i.e., SE, ME, helicopters, and ultralight aircraft) that are based at a given airport was used to help estimate the number of LTOs conducted by each category of activity (GA or AT) out of the total number of LTOs conducted at that airport. Airports lacking data on both the number of LTOs and the number of based aircraft were assigned 1 LTO per year based on a review of available information. For more information, see Sections 4a and 4b of: http://nepis.epa.gov/Exe/ZyPDF.cgi/P1009I13.PDF?Dockey=P1009I13.PDF.

[24] See Sections 4 and 6a of: http://nepis.epa.gov/Exe/ZyPDF.cgi/P1009I13.PDF?Dockey=P1009I13.PDF

[25] The method used to estimate piston-engine aircraft activity at specific runway ends has inherent uncertainty from both underlying operational data and local airport traffic patterns. Nevertheless, comparisons of the methodology presented here to airport-specific observations and data suggest that this method is appropriate for estimating piston-engine specific activity (See Section 3.3). EPA acknowledges that there are other methods to

from 2011 formed the basis of calculating activity at each runway end over 3-month rolling periods. Additional discussion on piston-engine activity in 2011 compared to other recent years is provided in Appendix B, Section 1. For a subset of airports, airport-specific data were used to provide an additional estimate piston-engine LTOs, as detailed in Section 3.3.

Annual GA and, separately, AT piston-engine LTOs at each US airport were separated into the four categories of the aircraft classes and cycle-types: SE full LTO, SE T&G, ME full LTO, and ME T&G, based on FAA data for GA and AT activity. Next, annual LTOs in each of these four categories at each airport were temporally allocated into daily and then hourly periods based on a combination of daily activity data from FAA and observations of hourly activity patterns at the model airport. The allocation of annual to daily piston-engine aircraft activity was accomplished by calculating a daily fraction of activity (i.e., GA or AT LTOs on a given day/annual GA or AT LTOs) for each airport. The daily fraction was then multiplied by the number of piston-engine LTOs in each of the four aircraft class and cycle-type categories. The resulting number of daily LTOs in each category was then allocated to each hour of each day based on a diurnal profile (i.e., fraction of daily LTOs per hour) from the model airport described in Section 2.2. Appendix B provides additional information on the diurnal profile observed at the model facility compared to observations at other airports.

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estimate piston-engine specific activity (Heiken et al. 2016), and that the national analysis focuses on activity estimates during a single year (2011), which does not capture the annual variability in piston-engine aircraft activity at each airport due to local circumstances or national trends.

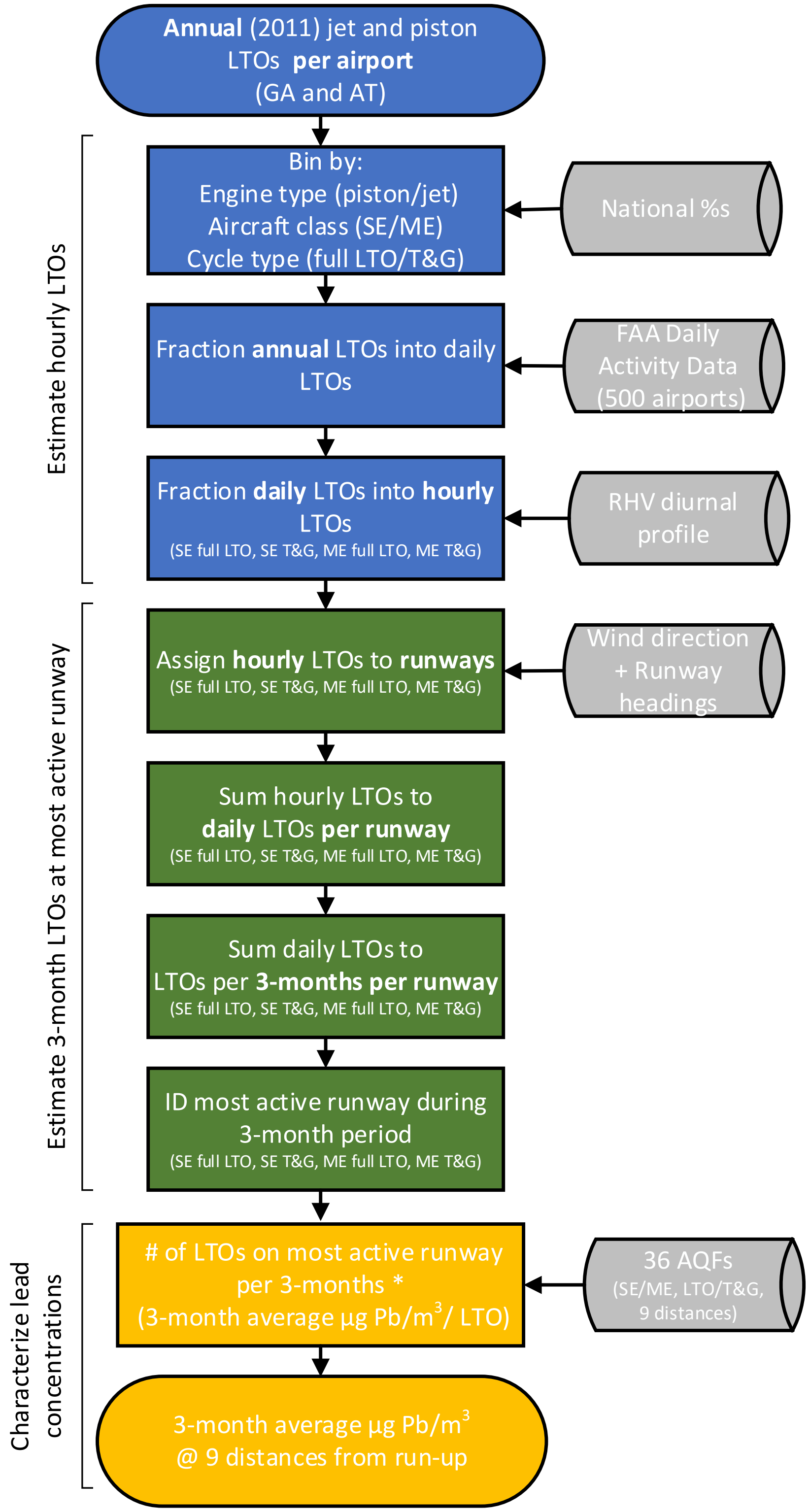

Figure 2. Overview of method to estimate piston-engine aircraft activity at airports nationwide. Center rectangles represent main calculation steps, while colors denote different spatial granularity. Grey cylinders represent input datasets. See Table 2 for details.

With the number of piston-engine LTOs (categorized as SE full LTO, SE T&G, ME full LTO, ME T&G) per hour at each airport, the next step was to assign LTOs to specific runway ends at each airport. Hourly LTOs were assigned to the runway end at which piston-engine activity would occur based on wind direction data since piston-engine aircraft take-off and land into the wind (See Appendix B for additional information on runway assignment and wind direction data).[26] Hourly LTOs per runway end were then summed to daily and, subsequently, rolling 3-month totals (aircraft class and cycle-type categories were maintained when aggregating up to 3-month LTOs). The total piston-engine LTOs per runway end in a 3-month period was then used to identify the most active runway at each airport. Next, the number of 3-month LTOs on the most active runway is multiplied by the appropriate AQF (e.g., number of 3-month SE full LTOs x SE full LTO AQF at maximum impact site) (Figure 3). As depicted in Equation 2, summing across the products from each of the four aircraft class and cycle-type categories provides a 3-month average, model-extrapolated concentration of lead in the maximum impact area and eight downwind locations for each of the approximately 13,000 airports. These model-extrapolated 3-month average lead concentrations are: 1) attributable to aircraft using leaded avgas, and 2) located at each of the nine specified distances at each US airport.

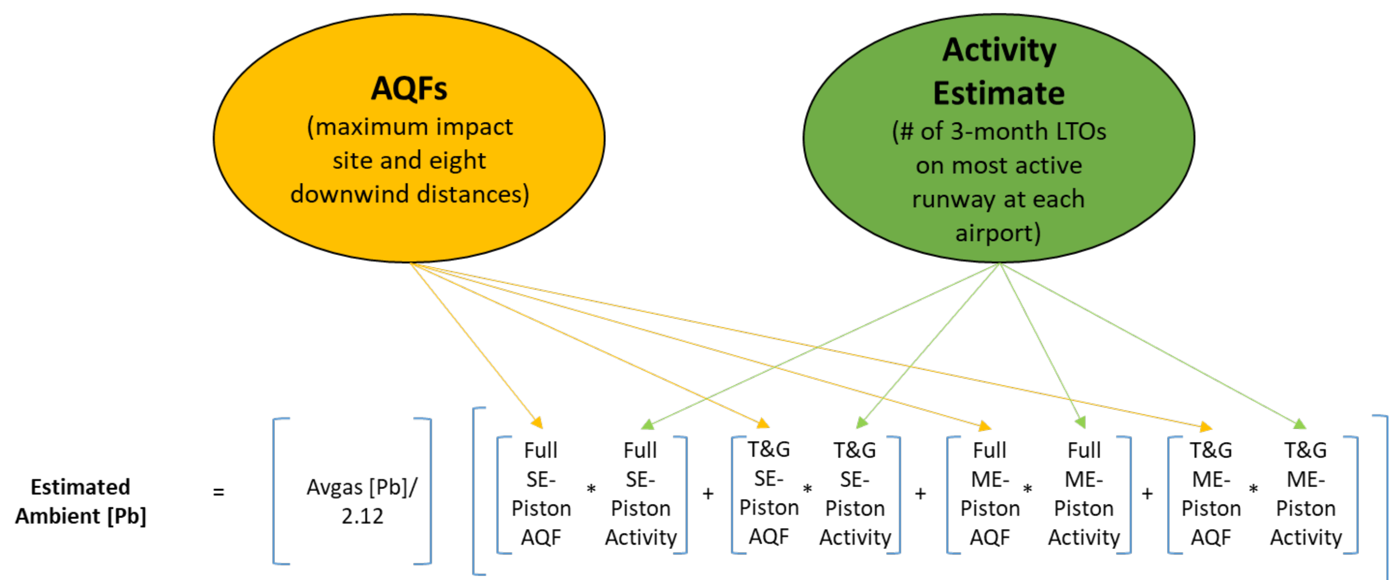

Figure 3. Visualization of approach for calculating extrapolated lead concentrations by multiplying emission factors (AQFs) by activity estimates for each airport nationwide using Equation 2.

[26] While piston-engine aircraft may conduct run-up and take-off on an alternative runway (i.e., not one facing into the wind) due to activity levels, weather, noise restrictions, or other airport operational considerations, wind is the primary driver of active runway selection Lohr, G. W. and D. M. Williams (2008). *Current practices in runway configuration management (RCM) and arrival/departure runway balancing (ADRB)*. NASA/TM-2008-215557 NASA. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090010329.pdf. Therefore, prevailing wind direction is an appropriate indicator for identifying which runway and direction piston-engine aircraft conduct take-off and landing operations. Runways are built to allow the maximum possible days of flying by taking into account the dominant wind direction(s) experienced at the airport; thus, the runway end(s) predominantly used for piston-engine aircraft take-off can be identified.

While several meteorological, geographical, and operational parameters may vary from conditions at the model airport or from the national default parameters used across the national analysis described above, wind speed is one meteorological parameter that clearly affects local concentration profiles of atmospheric aerosols. The model-extrapolated concentrations at and downwind of the maximum impact site as characterized in the approach above can be adjusted to better consider meteorological conditions by using inverse wind speed data over the 3-month maximum period. Specifically, the near-field concentration of a non-reactive pollutant scales with $\langle \boldsymbol{u}^{-1} \rangle$, where $\boldsymbol{u}$ is wind speed and angled brackets imply a time average (Barrett and Britter 2008). If the wind speed at the model airport is $\boldsymbol{v}$ and the wind speed at a specific airport is $\boldsymbol{u}$, then the wind-adjusted concentration would be the model-extrapolated concentration estimated by the methodology detailed above multiplied by the ratio of average inverse wind speeds $\langle \mathbf{v}^{-1} \rangle / \langle \mathbf{u}^{-1} \rangle$. If the wind speed at the specific airport is, in general, higher than the wind speed at the model airport where the AQFs were derived, then $\langle \mathbf{v}^{-1} \rangle$ would be less than $\langle \boldsymbol{u}^{-1} \rangle$ resulting in a lower concentration per activity at the specific airport than the AQF. Utilizing the same wind data that was used to assign operations to specific runways, model-extrapolated concentrations at airports nationwide can be adjusted for wind-speed, thereby appropriately characterizing concentrations at airports with significantly higher or lower wind speeds than the model airport. For the wind speed adjustment, wind speeds from 6am to 11pm[27] were averaged over the entire year at the model airport and for the 3-month maximum activity period at each US airport. As the inverse of wind speed tends toward infinity as wind speed tends toward zero, 0.5 m/s is chosen as a minimum allowable wind speed; this choice also aligns with ASOS station wind detection limits. Further details of the wind-adjustment approach are provided in Appendix A.

Results of the national analysis method and wind speed adjustment described here, and detailed in Table 2, are provided in Section 4. Additional quantitative and qualitative assessments of uncertainty from other potentially influential parameters, such as avgas lead concentration and seasonality of operational profiles are discussed in Section 3.4.

[27] These are the modeled hours from opening through one hour past closing for each airport, reflecting the times when atmospheric lead concentrations are expected to be highest.

Table 2. Steps to Calculate Airport Facility Specific Piston-Engine Aircraft Lead Concentrations

Step #	Step[28]	Description	Rationale	Data Source[29]
Steps 1 – 7 Objective: Estimate how much piston-engine activity occurred at each U.S. airport on an hourly basis, by engine, and operation type.				
1	**Estimate how much activity is conducted by piston-engine aircraft annually**	Estimate the annual number of piston-engine LTOs[30] in defined categories (i.e., GA and AT)	Only piston-engine aircraft use leaded avgas, thus we needed to estimate how much of the total activity at an airport was specific to piston-engine aircraft, rather than turbine-engine aircraft. While several data sources provide airport-specific aircraft activity data (separately for General Aviation (GA) and Air Taxi (AT) activity), none specifically identify the number of *piston-engine* aircraft LTOs that occur at each U.S. airport facility.	2011 NEI GA and AT piston-engine annual LTOs[31] (USEPA 2011)

[28] Each step in this table was carried out for the 13,153 airports in the US. Heliports and rotorcraft activity at airports were not included in this analysis; see Appendix B for additional information. For each of the 13,153 airports included in the analysis, calculations were completed for each day of 2011 and January – February 2012; however, annual estimates of piston-engine specific LTOs were only available for 2011, and thus estimates of piston-engine aircraft LTOs from January – February 2011 were used as surrogate activity data in the first two months of 2012. Based on the 2010 FAA Terminal Area Forecast (TAF), GA activity levels were similar between 2011 and 2012 (5% lower activity in 2012 than 2011) (https://taf.faa.gov/).

[29] Additional information on available FAA data sources is presented in Appendix B.

[30] An aircraft operation is defined as any landing or takeoff event, therefore, to calculate LTOs, operations are divided by two. Most data sources from FAA report aircraft activity in numbers of operations. Our air quality factors (AQFs), described in step 13, are in units of concentration per LTO, therefore for the purposes of this analysis, operations need to be converted to LTO events.

[31] The EPA 2011 NEI estimates annual GA and AT piston-engine LTOs that occur at each airport nationwide. These estimates were the starting point for this national analysis of lead concentrations at and downwind of maximum impact sites at airports nationwide. The general approach to estimate piston-engine aircraft LTOs in the 2011 NEI is briefly outlined here with more details are available in Sections 1, 3, 4, and 6a of the NEI documentation USEPA. (2011). "2011 National Emissions Inventory (NEI) Data." 2017, from http://www.epa.gov/air-emissions-inventories/2011-national-emissions-inventory-nei-data. In particular, the 2011 NEI used based aircraft, reported as single- or multi-engine, to develop more airport-specific piston-engine LTOs at airports with the potential for lead air emissions inventories greater than 0.50 tons per year. In the national analysis, based aircraft are similarly used to develop more airport-specific results for airports with model-extrapolated concentrations in the upper range of those nationwide (see Section 3.3 for details).

Step #	Step[28]	Description	Rationale	Data Source[29]
1a	For GA activity	The national average percent of GA activity that was conducted by piston-engines (72%), according to the 2010 FAA GAATA report, was multiplied by total GA LTOs at each airport.	Multiplying GA LTOs at an airport by the national average of GA LTOs conducted by piston-engine aircraft was necessary to estimate the annual number of GA *piston-engine* LTOs that occurred at each airport.	2011 NEI GA piston-engine annual LTOs & FAA GAATA, 2010 (FAA 2010)
1b	For AT activity	The national average percent of AT activity that was conducted by piston-engines (23%), according to the 2010 FAA GAATA report, was multiplied by total AT LTOs at each airport.	Multiplying AT LTOs at an airport by the national average of AT LTOs conducted by piston-engine aircraft was necessary to estimate the annual number of AT *piston-engine* LTOs that occurred at each airport.	2011 NEI AT piston-engine annual LTOs & (FAA 2010)
Result: <u>**Annual**</u> number of GA piston-engine LTOs and AT piston-engine LTOs at each U.S. airport				
2	**Estimate how much of the annual piston-engine aircraft activity is conducted by each piston-engine aircraft class, performing different cycle-types**	Estimate the number of total annual piston-engine LTOs that are conducted by specific aircraft classes (i.e., SE and ME for specific cycle-types (i.e., Full LTO and T&G) at each airport.	Different aircraft classes and cycle-types have different fuel consumption rates, and therefore different quantities of lead emissions.	
2a	For GA piston-engine LTOs	Multiply the annual number of GA piston-engine LTOs (from Step 1a) by the national fraction of annual GA activity conducted by each aircraft class and cycle-type (i.e., SE Full LTO, SE T&G, ME Full LTO, ME T&G).	Fractioning GA piston-engine activity into 4 combinations of aircraft and cycle-types (i.e., 68% SE Full LTO, 23% SE T&G, 8% ME Full LTO, 2% ME T&G) allows us to categorize LTOs by sub-type of GA piston-engine activity which is important since each sub-type	Step 1a &

Step #	Step[28]	Description	Rationale	Data Source[29]
			impacts the resulting concentrations differently.	(FAA 2010)(Table 1.4)[32]
2b	For AT piston-engine LTOs	Multiply the annual number of AT piston-engine LTOs (from Step 1b) by the national fraction of annual AT activity conducted by each aircraft class and cycle-type (i.e., SE Full LTO, SE T&G, ME Full LTO, ME T&G).	Fractioning AT piston-engine activity into 4 combinations of aircraft classes and cycle-types (i.e., 57% SE Full LTO, 0% SE T&G, 43% ME Full LTO, 0% ME T&G) allows us to categorize LTOs by sub-type of AT piston-engine activity, which is important since each sub-type impacts the resulting concentrations differently.	Step 1b & (FAA 2010) (Table 1.4)
Result: <u>**Annual**</u> number of piston-engine LTOs at each U.S. airport categorized as: 1) GA SE Full LTO, 2) GA SE T&G, 3) GA ME Full LTO, 4) GA ME T&G, 5) AT SE Full LTO, 6) AT SE T&G, 7) AT ME Full LTO, 8) AT ME T&G.				
3	**At the U.S. towered airports, estimate what fraction of annual activity occurred on each day of the analysis (separately for GA and AT)** [33]	Approximately 500 airports have air traffic control towers (i.e., are "towered airports") and therefore have daily activity counts (separate for GA and AT). At each of these airports we developed separate GA and AT daily activity profiles, or fractions of annual activity that occurred during each day of the analysis. These daily activity	Steps 1 – 2 provide <u>annual</u> piston-engine activity; however, aircraft activity varies by month, day, and hour. Because of this temporal variability, identifying the maximum 3-month period of activity necessitates that we apportion the annual activity data to daily activity (this step) and subsequently (in the following steps) further apportion daily data to each hour of the day.	ATADS

[32] The 2011 FAA GAATA report was not published, therefore the 2010 FAA GAATA report was used for this step. Based on a comparison of the 2010 and 2012 FAA GAATA reports, engine and operation type splits were very similar between 2010 and 2012 (<1% difference in any category between 2012 than 2010) (https://www.faa.gov/data_research/aviation_data_statistics/general_aviation/). See Section 4 for additional discussion on uncertainty and variability in data used in this analysis. The full LTOs and T&Gs fractions were based on the number of hours flown for GA or AT activities where T&Gs were defined as the percent of "instructional" hours and full LTOs were defined as the percent of all remaining hours (e.g., total GA hours flown – instructional hours). The amount of instructional activity will vary by airport. For instance, T&G activity was 4.5 to 29% and 0 to 35% of total SE and ME LTOs, respectively at airports for which EPA has conducted onsite observational surveys (see Appendix C for survey details).

[33] For example, the number of GA operations at each towered airport on January 1, 2011 (from ATADS dataset) were divided by each airport's respective total number of GA operations in 2011. All operational data were converted to LTOs by dividing by two (i.e., two operations is one LTO).

Step #	Step[28]	Description	Rationale	Data Source[29]
		profiles will later be applied to all U.S. airports (see Step 5).		
3a	For GA LTOs	At each towered airport, divide daily GA LTOs for each day included in the analysis by annual GA LTOs to reach the daily fraction of GA LTOs at each towered airport.	Dividing daily by annual GA activity produces a daily GA activity profile for each towered airport.	ATADS
3b	For AT LTOs	At each towered airport, divide daily AT LTOs for each day included in the analysis by annual AT LTOs to reach the daily fraction of AT LTOs at each towered airport.	Dividing daily by annual AT activity produces a daily AT activity profile for each towered airport.	ATADS
Result: **Daily** Activity Profiles, separately for GA and AT activity, at each towered airport for each day in the analysis.				
4	**For each non-towered U.S. airport, identify its closest towered airport**	Use latitude/longitude data and a distance formula to determine the closest towered airport to each non-towered U.S. airport.[34] These data will be used in combination with the daily activity profiles calculated in step 3 to estimate daily piston activity at each U.S. airport.	Data to develop daily activity profiles are only available for airports that report daily activity data (i.e., towered airports). To apportion each airport's annual activity to individual days, we apply the daily profile from the towered airport closest in distance to the non-towered airport. To do so, we first determine the closest towered airport for each non-towered U.S. airport. [35]	FAA 5010
Result: Identification of the closest towered airport for each non-towered airport in the U.S.				

[34] For two airports with (latitude, longitude) pairs of (LatA, LongA) and (LatB, LongB), the distance between them will be:
distance (km) = R*arccos[cosd(LatA)*cosd(LatB)*cosd(LongB-LongA)+sind(LatA)*sind(LatB)] where R is the radius of the spherical approximation of Earth.

[35] Airport towers at the 500 most active airports in the U.S. report the number of total operations on each day, which are recorded in the FAA ATADS database. For airport facilities without ATADS data, we used activity data from the nearest ATADS facility as a surrogate for the airport facility without daily activity data (distances between ATADS facility and surrogates: Mean 64 km, Max 672 km, 25th % 28 km, 75th % 79 km, 90th % 128 km, 95th % 169km, 99th % 292 km). The closest towered airport to a towered airport will be itself. Note that primary airports (i.e., airports with mainly commercial jet activity) were not used as surrogates since these airports likely have a distinctly different activity profile than GA airports. (See Appendix B for additional details on the ATADS database.)

Step #	Step[28]	Description	Rationale	Data Source[29]
5	**Estimate the number of daily piston-engine** LTO**s at all U.S. airports**	Multiply each airport's annual activity (step 2) by the daily activity profile (step 3) for its closest towered airport. This is done separately for GA and AT.	The GA and AT daily activity profiles (step 3) allow us to apportion annual activity into daily activity.	
5a	For GA LTOs	Multiply each airport's annual piston-engine GA activity (for each of the 4 types: 1) GA SE Full LTO, 2) GA SE T&G, 3) GA ME Full LTO, 4) GA ME T&G) by the GA daily activity profile for its closest towered airport.	Daily activity data are only available for the combined set of all GA aircraft engine & operation types (i.e., SE Full LTO, SE T&G, ME Full LTO, ME T&G), thus, we use the same GA daily activity profile for each of the 4 subsets of GA activity at all airports.	Steps 2a & 3a
5b	For AT LTOs	Multiply each airport's annual piston-engine AT activity (for each of the 4 types: 1) AT SE Full LTO, 2) AT SE T&G, 3) AT ME Full LTO, 4) AT ME T&G) by the AT daily activity profile for its closest towered airport.	Similar to GA, daily activity data are only available for all types of AT aircraft engine & operation types (i.e., SE Full LTO, SE T&G, ME Full LTO, ME T&G) combined, thus, we use the same AT daily activity profile for each of the 4 subsets of AT activity at all airports.	Steps 2b & 3b
Result: Number of <u>**daily**</u> piston-engine LTOs at each U.S. airport categorized as: 1) GA SE Full LTO, 2) GA SE T&G, 3) GA ME Full LTO, 4) GA ME T&G, 5) AT SE Full LTO, 6) AT SE T&G, 7) AT ME Full LTO, 8) AT ME T&G.				
6	**Sum the number of daily** LTO**s by aircraft engine type & operation mode**	Sum the daily number of GA and AT LTOs across aircraft engine and operation type (i.e., SE Full LTO, SE T&G, ME Full LTO, ME T&G).	The concentration of lead emissions is related to the type of aircraft engine and operation type, thus there is no distinction in terms of emissions between a SE Full LTO conducted as GA vs. AT. Understanding levels of GA vs. AT activity was necessary to appropriately apportion annual GA and AT activity into specific piston engine and operation types.	Step 5
6a	For SE full LTO	Sum the # of GA SE full LTOs & # of AT SE full LTOs for each day at each airport.		
6b	For SE T&G	Same as Step 6a but for SE T&G.		
6c	For ME full LT0	Same as Step 6a but for ME full LTO.		
6d	For ME T&G	Same as Step 6a but for ME T&G.		

Step #	Step[28]	Description	Rationale	Data Source[29]
Result: Number of **daily** piston-engine LTOs at each U.S. airport categorized as: 1) SE Full LTO, 2) SE T&G, 3) ME Full LTO, 4) ME T&G				
7	**Estimate the number of** LTOs **that occurred during each hour of each day (i.e., the distribution of** LTOs **across facility operational hours of the day)**	For each day at each U.S. airport, multiply the number of daily piston-engine LTOs (separated into 1) SE Full LTO, 2) SE T&G, 3) ME Full LTO, 4) ME T&G) by the corresponding hourly activity profile (i.e., % of daily aircraft LTOs that occurred during each operational hour) from the model airport. There are separate profiles for each engine type (1) SE Full LTO, 2) SE T&G, 3) ME Full LTO, 4) ME T&G) by weekday/weekend status.[36] (e.g., If 30% of SE Full LTOs occurred during Hour 5 on a weekday at the representative facility, and 10 SE Full LTOs occurred at a given facility on Day 1 (a weekday) of the analysis, then 3 SE Full LTOs would be assigned to Hour 5 of Day 1 at the given facility).	Step 6 results in daily piston-engine activity; however, aircraft activity varies by month, day, and hour. Because of this temporal variability, identifying the maximum 3-month period of activity necessitates that we apportion the daily activity data to hourly activity (this step). Subsequently (in the following step), we use wind direction data to apportion the hourly data to specific runway ends at each airport.	Model airport (see Section 2 & Appendix A) & Step 6
7a	For weekdays		Since data we collected suggests that the distribution of piston-engine aircraft activity can vary between weekend and weekdays, we used an activity distribution representative of weekday activity, and separately, an activity distribution for weekend activity.	Appendix A & Step 6

[36] For more information on the distribution of LTOs over operational hours at the model airport see Appendix A. We characterize the influence of using a different distribution of LTOs across the day on estimates of ambient lead in Appendix B.

Step #	Step[28]	Description	Rationale	Data Source[29]
7ai	For SE Full LTO	Multiply % of SE Full LTOs that occurred in each operational hour of a weekday at a representative facility by the number of daily SE Full LTOs for each facility in the analysis; repeat for each day in the analysis.		
7aii	For SE T&G	Repeat Step 7ai for SE T&G.		
7aiii	For ME Full LT0	Repeat Step 7ai for ME Full LT0.		
7aiv	For ME T&G	Repeat Step 7ai for ME T&G.		
7b	For weekends	Repeat Steps 7ai – 7aiv using the distribution of LTOs across operational hours on a weekend day.		Appendix A & Step 6
Result: Number of **hourly** piston-engine LTOs that occurred on each day of the analysis at each U.S. airport, categorized as: 1) SE Full LTO, 2) SE T&G, 3) ME Full LTO, 4) ME T&G				
Steps 8 – 12 Objective: Estimate how much piston-engine activity occurred on each runway end over each rolling 3-month period.				
8	**Identify the runway end at which aircraft activity likely occurred for each hour of each day in the analysis**	Use wind direction data for each hour that an airport is open (i.e., operational hours)[37] to identify the runway end on which piston-engine aircraft LTOs were conducted; repeat for each day in the analysis.	Piston-engine aircraft take-off into the wind, thus wind direction dictates the runway end that is used; wind direction can change throughout the day so we evaluate hourly wind direction[38] to identify the runway end used predominantly for each hour.	ASOS wind tower with shortest distance to airport
8a	For each U.S. airport, determine	Use latitude/longitude data and distance formula[39] to determine the	Hourly wind direction data was available at the 938 ASOS stations, most of which are	ASOS and FAA 5010

[37] Operational hours were defined as 6 a.m. to 10 p.m. for all airport facilities in the analysis. While some airport facilities may have slightly different operational hours (e.g., open 6 a.m. to 11 p.m.), the operational hours selected for the analysis are likely representative of most airport facilities based on review of operational hours at numerous airports (www.airnav.com).

[38] The hourly wind direction data used in this analysis is the result of 1-min wind data having been processed by EPA's AERMINUTE into hourly wind data (see section 4.6 of AERMINUTE User's Guide for averaging method: https://www3.epa.gov/ttn/scram/7thconf/aermod/aerminute_userguide.pdf

[39] See footnote 30 for distance formula.

Step #	Step[28]	Description	Rationale	Data Source[29]
	its closest ASOS station	closest ASOS station to each U.S. airport.[40]	located at airports.[41] To determine runway usage based on wind direction data, we first determined the closest ASOS station to each U.S. airport.	(See Appendix B for details)
8b	Use the hourly wind direction data from an airport's closest ASOS station to determine which runway end was used for each hour of the analysis	See Appendix B for details.	In order to appropriately estimate the location of the maximum lead concentration from piston-engine activity, we use wind direction data to identify where activity occurred (i.e., which runway end).	
Result: Location (i.e., runway end) of aircraft activity at each U.S. airport during each hour of each day in the analysis				
9	**Determine number of** LTO**s that occurred on each runway end on an** <u>**hourly**</u> **basis**	Assign piston-engine aircraft LTOs in each hour (Step 7) to the runway end that was active during each hour (Step 8); repeat for each day in the analysis.	Merging information regarding the *number* of hourly LTOs (Step 7) with our assessment of hourly *runway usage* (i.e., which runway end was used during each hour) allows us to quantify the hourly number of LTOs that occurred on each runway end at each U.S. airport for each day of the analysis.	
9ai	For SE Full LTO	Assign SE Full LTOs in each hour (Step 7) to the runway end that was active during each hour (Step 8); repeat for each day in the analysis.		Steps 7 & 8
9aii	For SE T&G	Repeat Step 9ai for SE T&G.		
9aiii	For ME Full LT0	Repeat Step 9ai for ME Full LT0.		
9aiv	For ME T&G	Repeat Step 9ai for ME T&G.		
Result: Number of piston-engine LTOs that occurred during each <u>hour</u> on each <u>runway</u> end during each day of the analysis at each U.S. airport, categorized as: 1) SE Full LTO, 2) SE T&G, 3) ME Full LTO, 4) ME T&G				

[40] The closest ASOS station to an airport with an ASOS station will be its own station.
[41] ASOS & Climate Observations Fact Sheet. November 2012. U.S. NOAA

Step #	Step[28]	Description	Rationale	Data Source[29]
10	**Determine the number of** LTOs **that likely occurred on each runway end on a daily basis**	For each runway end at each airport, sum the number of aircraft LTOs that occurred during all operational hours for a given day; repeat for each day in the analysis.	To estimate the number and type of LTOs that occurred at an airport on each runway end over an entire day, we sum the hourly LTOs, by runway end. In subsequent steps we use this daily information to estimate activity over 3-month time periods, which corresponds to the lead NAAQS averaging period.	
10ai	For SE Full LTO	For each runway end at each airport, sum the number of SE Full LTOs that occurred during all operational hours for a given day; repeat for each day in the analysis.	Summing all of the SE Full LTOs at an airport that occurred at each runway end during each operational hour of a day allows us to estimate the number of SE Full LTOs that occurred on each day of the analysis at each runway at an airport.	Step 9
10aii	For SE T&G	Repeat Step 10ai for SE T&G.		
10aiii	For ME Full LT0	Repeat Step 10ai for ME Full LT0.		
10aiv	For ME T&G	Repeat Step 10ai for ME T&G.		
Result: Number of piston-engine LTOs that occurred during each day on each runway end at each U.S. airport, categorized as: 1) SE Full LTO, 2) SE T&G, 3) ME Full LTO, 4) ME T&G				
11	**Sum daily # of** LTOs **estimated to have occurred on each runway end by rolling 3-month period**		We estimate the number and type of LTOs that occurred on each runway end at each airport over a rolling 3-month period using the daily information generated in Step 10, since the averaging time for the lead NAAQS is a rolling 3-month averaging period (e.g., January – March, February – April, March – May).[42]	

[42] At some airports available data suggest that the sum of LTOs in the 3-month period is less than one; this is predominantly due to the airport having fewer than 5 LTOs per year, but in some cases, may be due to missing data (e.g., runway end identifiers). Low activity or a lack of data resulted in 2,095 out of the 13,000 airports nationwide with less than one LTO in the 3-month period. Model-extrapolated concentrations at these airports are thus less than 0.0075 ug/m^3

Step #	Step[28]	Description	Rationale	Data Source[29]
11ai	For SE Full LTO	For each runway end at each airport, sum the number of SE Full LTOs that occurred during each day of a 3-month period; repeat for each rolling 3-month period included in the analysis.		Step 10
11aii	For SE T&G	Repeat Step 11ai for SE T&G.		
11aiii	For ME Full LT0	Repeat Step 11ai for ME Full LT0.		
11aiv	For ME T&G	Repeat Step 11ai for ME T&G.		
Result: Number of piston-engine LTOs that occurred during each rolling 3-month period on each runway end at each U.S. airport, categorized as: 1) SE Full LTO, 2) SE T&G, 3) ME Full LTO, 4) ME T&G				
12	**Identify the runway end with the highest estimates of piston-engine aircraft activity during any 3-month period at each airport**		Piston-engine aircraft activity is a first-order determinant of lead concentrations in the maximum impact area in monitoring and modeling studies, as described in Section 2, and thus the period of maximum activity is assumed to represent the period of maximum concentration. [43]	Step 11
12a	For each runway end, sum the number of total piston aircraft LTOs that occurred during each 3-month period for all engine & operation types; repeat for	Sum Steps 11ai – 11aiv by runway and by 3-month period for each U.S. airport.	In addition to understanding how much piston-engine aircraft activity of specific engine class & cycle types occurred at each runway end over rolling 3-month periods (which will be used in Step 13), we to need identify the runway end at which the most piston aircraft activity of any type was conducted over a rolling 3-month period. Identifying the runway end used most	Step 11

(see Section 4.1 for results). Additional analyses outside the scope of this report would be needed to evaluate airborne lead concentrations at these individual airports.

[43]In some instances, meteorological parameters (e.g., low mixing height) may result in maximum concentrations during relatively lower activity periods. Uncertainty and variability in meteorological parameters is discussed further in Section 4.3.

Step #	Step[28]	Description	Rationale	Data Source[29]
	each rolling 3-month period included in the analysis		frequently by piston-engine aircraft allows us to estimate ambient concentrations at the location (i.e., runway end) with the most piston-engine activity, and in turn the highest lead emissions.	
12b		Review number of piston-engine LTOs conducted at each runway end during each rolling 3-month period included in the analysis and identify the runway end with the most total piston-engine LTOs during any 3-month period; repeat for each airport facility in the analysis.		Step 12a
Result: Identification of the most active runway during any 3-month period at each airport facility included in the analysis				
Steps 13 – 15 Objective: Estimate maximum 3-month lead concentrations from Piston-engine aircraft at each U.S. Airport				
13	**Estimate ambient lead concentrations from piston-engine aircraft lead emissions at the runway end most frequently used by piston-engine aircraft during the most active rolling 3-month period**	Multiply the number of LTOs that occurred on the runway end most frequently used by piston-engine aircraft during the most active 3-month period by corresponding air quality factors; repeat for each facility in the analysis.	In Steps 1 – 12 we estimate piston-engine aircraft activity (i.e., how many LTOs of which engine class and cycle type that occur when and where) at each airport facility included in the analysis. We then combine our activity estimates with estimates of lead concentrations associated with each type of LTO in order to calculate total maximum 3-month lead concentrations from piston-engine aircraft. To do so, we use AQFs that are specific to each engine class and cycle type (SE Full LTO, SE T&G, ME Full LTO, ME T&G).	
13ai	For SE Full LTOs at the most active runway during the	Multiply the following: 1) the number of SE Full LTOs that occurred at the runway end most frequently used by piston-engine	As described in Section 3.1, AQFs are the relationship of lead concentration per unit of aircraft activity (with distinct AQFs for each aircraft engine and operation type) and	Steps 11&12; Model airport (see

Step #	Step[28]	Description	Rationale	Data Source[29]
	most active 3-month period	aircraft during the most active 3-month period, by 2) the AQF for SE Full LTOs at the max impact site; repeat for each facility in the analysis.	having units of average 3-month µg Pb/ m^3/ LTO. By multiplying each AQF by the level of activity we estimate the lead concentration (µg Pb/ m^3) associated with the number of LTOs we estimated in Steps 1 – 12.	Section 2 & Appendix A)
13aii	For SE T&G	Repeat Step 13ai for SE T&G.		
13aiii	For ME Full LT0	Repeat Step 13ai for ME Full LT0.		
13aiv	For ME T&G	Repeat Step 13ai for ME T&G.		
13av	For all piston-engine activity	Sum Steps 13ai – 13aiv.	We need to understand total lead concentrations from all types of piston-engine activity, which is the sum of Steps 13ai-13aiv.	
13avi	Scaled by the lead concentration in avgas	First, divide the ASTM standard for Pb concentration in avgas (2.12 g Pb/gal) by the avgas Pb concentration at the model airport (2.16 g Pb/gal). Second, multiply the ratio of 2.12/2.16 by the sum of lead concentration from all types of piston-engine activity (Step 13av).	The AQFs were generated at a model airport with a concentration of Pb in avgas that is different from the ASTM maximum specification for this fuel. Thus, we scale the lead concentrations at each airport by the ratio of the ASTM standard lead concentration to the avgas lead concentration at the facility used to develop AQFs.[44]	
Result: Ambient lead concentration estimates at the max impact site at the most active runway end during the most active 3-month period for each airport facility included in the analysis				
14	**Estimate ambient lead concentrations at locations further downwind from the runway end**	Repeat Step 13 with the appropriate AQFs for the 8 locations further downwind of the max impact site (50, 100, 150, 200, 250, 300, 400, 500 m); repeat for each facility included in the analysis.	As discussed in Section 3.1, in addition to developing AQFs at the max impact site, we also developed AQFs at 8 locations downwind of the max impact site (i.e., where piston-engine aircraft conduct run-up checks) in order to provide estimates of how lead concentrations change with distance. Similar	Model airport (see Section 2 & Appendix A)

[44] We examine the influence that using the ASTM standard for avgas lead concentration has on our ambient lead concentration estimates in Section 4.

Step #	Step[28]	Description	Rationale	Data Source[29]
			to Step 13, we need to combine each respective AQF with activity estimates in order to estimate concentrations of ambient lead at each distance for each airport included in the analysis.	
Result: Ambient lead concentration estimates at 8 locations downwind of the max impact site at the most active runway end during the most active 3-month period for each airport included in the analysis				
15	**Estimate wind-adjusted ambient lead concentrations using average inverse wind speed**	Scale the model-extrapolated ambient lead concentrations by the ratio of the average inverse wind speeds at the model airport to the average inverse wind speeds recorded at the nearest ASOS wind tower.	As discussed in Section 3.2, wind speed has a consistent and well-characterized impact on the near-field concentration of a passive tracer under dispersion. Therefore, scaling model-extrapolated lead concentrations to consider wind speed will better characterize local concentrations at airports nationwide, particularly those airports where wind speeds during the maximum activity period differ significantly from those observed at the model airport.	Appendix A and ASOS wind tower with shortest distance to airport
Result: Ambient wind-adjusted lead concentration estimates at and downwind of the max impact site at the most active runway end during the most active 3-month period for each airport included in the analysis				

3.3 Evaluation of Airports for Potential Lead Concentrations Above the Lead NAAQS

The national analysis methods described in Section 3.2 provided estimates of 3-month average model-extrapolated lead concentrations in the maximum impact area and locations downwind out to 500-meters for 13,153 airports. Within this large set of model-extrapolated concentrations, we identified the subset of airports where lead concentrations were estimated to potentially approach, within 10%, or to be above the lead NAAQS.[45] To do this, we first identified airports where model-extrapolated concentrations were above the NAAQS. Next, we ran a series of sensitivity analyses to identify any additional airports where model-extrapolated concentrations may be above or approach the NAAQS when considering the major drivers of airport-to-airport variability and uncertainty. For this subset of airports, we then identified additional, airport-specific data that could refine the estimates of piston-engine aircraft activity. Finally, for this subset of airports we considered additional airport-specific criteria, such as the unrestricted access within 50 meters of the maximum impact location. An overview and rationale for the approach is provided in Section 3.3.1 followed by a description of how we adjusted activity estimates for the identified subset of airports using airport-specific data in Section 3.3.2. The full methodology for considering concentrations using airport-specific activity data and additional criteria is presented in Section 3.3.3.

3.3.1 Sensitivity Analysis of Airport-Specific Parameters that Influence Potential for Lead Concentrations to be Above the NAAQS

The first step to identify airports at which model-extrapolated concentrations are potentially above the lead NAAQS was to evaluate which airport-specific parameters may result in uncertainty or bias that would lead to underestimates in model-extrapolated concentrations from the national analysis methods presented in Section 3.2. There is potential uncertainty and/or bias from using national defaults for: 1) percentages of piston aircraft at an airport, 2) percentages of piston operations performed by single- versus multi-engine aircraft, and 3) assigning piston operations to runway ends. To address these sources of uncertainty and to identify airports where lead concentrations may approach or be above the NAAQs, but would not be identified by using national defaults, we conducted a series of sensitivity analyses. These sensitivity analyses expand the number of airports that would be within 10% of the NAAQs by using different assumptions for each of the three parameters outlined above that used national defaults in the national analysis.

For the first two parameters, we accounted for the possibility that the percentage of activity conducted by piston-engine aircraft and/or the percentage of piston-engine aircraft activity conducted by multi-engine aircraft at each airport might be underestimated by national averages. We did so by evaluating a scenario in which all GA and half of AT activity was conducted by piston-engine aircraft at each airport (i.e., we substituted 100% and 50% for the national average percentages of 72% and 23% piston-engine aircraft of total GA and AT,

[45] The current NAAQS for lead is 0.15 μg/m^3 as a 3-month rolling average. For this analysis, "approaching" the lead NAAQS is defined as within 10% of the current standard, or 3-month average model-extrapolated concentrations ≥0.14 μg/m^3.

respectively; see Step 1 of Table 2).[46] Because AT operations are more often conducted by ME aircraft, this sensitivity analysis impacts both the estimates of piston-engine aircraft activity and the predominance of ME or SE piston-engine aircraft at an airport. We then identified airports that had 3-month average model-extrapolated lead concentrations that were within 10% of the lead NAAQS after accounting for the possibility that national averages might be under-representations of piston-engine activity at some airports.

An additional sensitivity analysis was performed on the percentage of operations that occur at the most-utilized runway during the maximum activity period (Step 12 of Table 2). Two factors contribute to this percentage: the seasonal profile of operations and the allocation of operations to different runways based on wind direction. For the airports that were identified as having maximum 3-month concentrations above or approaching 0.15 $\mu g/m^3$ through the national analysis method presented in Section 3.2, the average percentage of annual activity occurring at the maximum period runway end is 20%. However, this percentage ranges from <6% at some airports, up to 45% at others. Reasons why an aircraft could take-off or land on a runway end other than the one assigned in the extrapolation, or be active during another 3-month period, include that the airport's seasonal profile of piston operations differs from that of the nearest ATADS airport, or the airport has two runways with similar headings, such that the dominant wind direction bisects them. These effects could bias estimates of operations and therefore concentrations either high or low. To better understand if some airports could have concentrations approaching or above the NAAQs that were not identified in the initial nationwide analysis due to a runway assignment bias, a sensitivity analysis was performed; airports that had less than 20% of their operations occurring at their maximum utilized 3-month period runway end were changed to having 20% of operations occur at that runway during that period.[47]

Additional sources of uncertainty in operational data that could impact the national analysis results are discussed in Section 4.4 of this report. For example, there may be uncertainty in the annual GA operations counts that underlie the piston operations data. However, changing the total annual GA operations count effects the resulting maximum concentrations in the same way that changing the percentage of GA operations that are conducted by piston aircraft effects the maximum concentration (i.e., increasing total GA operations by 10% would be analytically equivalent to keeping GA operation counts constant and increasing the percentage

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[46] The parameters presented in these sensitivity analyses, such as the 100% GA and 50% AT activity conducted by piston-engine aircraft, were only used to identify airports for additional analysis; neither these parameters nor the resulting maximum 3-month concentrations were used in the airport-specific activity analysis described below and presented in Section 4.2.

[47] This sensitivity analysis may not identify all airports where maximum concentrations have been under- (or over-) estimated due to the operational profile and runway assignment methodology. For example, an airport that the national analysis identifies as having 21% of operations occurring at the maximum runway end may in practice have 35% of operations occurring at that runway end. However, initial analysis showed that model-extrapolated concentrations estimated to be above the level of the lead NAAQS were mostly insensitive to operational shifts of this scale. This suggests that the national analysis methodology is appropriate for identifying airports with the potential for model-extrapolated concentrations to be above the lead NAAQS even considering this operational uncertainty.

performed by piston aircraft by 10%). Thus, the sensitivity analyses performed above may be interpreted to account instead, at least in part, for independent uncertainty from these other sources.

The airports identified in the national analysis or sensitivity analyses as having maximum 3-month concentrations above or approaching the NAAQS were the focus of a more refined assessment of piston-engine aircraft activity, as described below.

3.3.2 Airport-Specific Activity Data

The objective of the sensitivity analyses described above was to identify additional airports at which it would be informative to evaluate airport-specific piston-engine aircraft activity data, rather than national average data. The above sensitivity analyses applied alternative default assumptions for two parameters to all 13,000 airports, while the analyses in this section apply airport-specific data to the subset of airports identified through the sensitivity analyses and the national analysis. The objective of the analyses in this section is to account for the fact that national average activity estimates may potentially be improved by using airport-specific activity surrogates. As described in Section 3.2, piston-engine aircraft activity is not reported for individual airports, thus estimates of activity specific to piston-engine aircraft were calculated using national averages for the fraction of total GA and AT LTOs conducted by piston-engine aircraft. Similarly, national average fractions were used to estimate piston-engine LTOs conducted by SE versus ME aircraft. Both of these parameters (piston-engine aircraft activity and SE versus ME activity) particularly influenced monitored and modeled lead concentrations attributable to piston-engine aircraft in previous analyses conducted by EPA and others (Fine et al. 2010, Carr et al. 2011, Heiken et al. 2014, Feinberg et al. 2016). In these analyses, piston-engine aircraft activity had a direct impact on lead concentration, where more piston-engine aircraft activity (i.e., more LTOs) generally correlated with higher lead concentrations (Figure 4 provides one example of this relationship at Palo Alto Airport (PAO), which was included in EPA NAAQS lead surveillance monitoring network).

Additionally, sensitivity analyses conducted at two GA airports (RHV and SMO), showed that the amount of activity conducted by multi-engine piston aircraft had a disproportionately larger impact on lead concentrations compared with single-engine aircraft activity (see Appendix B; (Carr et al. 2011)). [48] Based on the important influence of these two parameters in previous analyses, additional, airport-specific information was gathered to further characterize total piston-engine aircraft activity and the percentage of activity conducted by single- versus multi-piston-engine aircraft at each of the airports included in this refined, airport-specific activity analysis.[49]

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[48] Multi-engine (ME) piston aircraft have a higher fuel consumption rate compared to single-engine (SE) piston aircraft; thus, LTOs conducted by ME aircraft result in higher lead concentrations.

[49] Total landing and take-off counts, the percentage split between piston and non-piston aircraft, and the runway assignment method may also each contribute to uncertainty in counts of piston-engine aircraft LTOs at a given runway end. The runway assignment method and its impact on LTO counts is discussed in Appendix B.

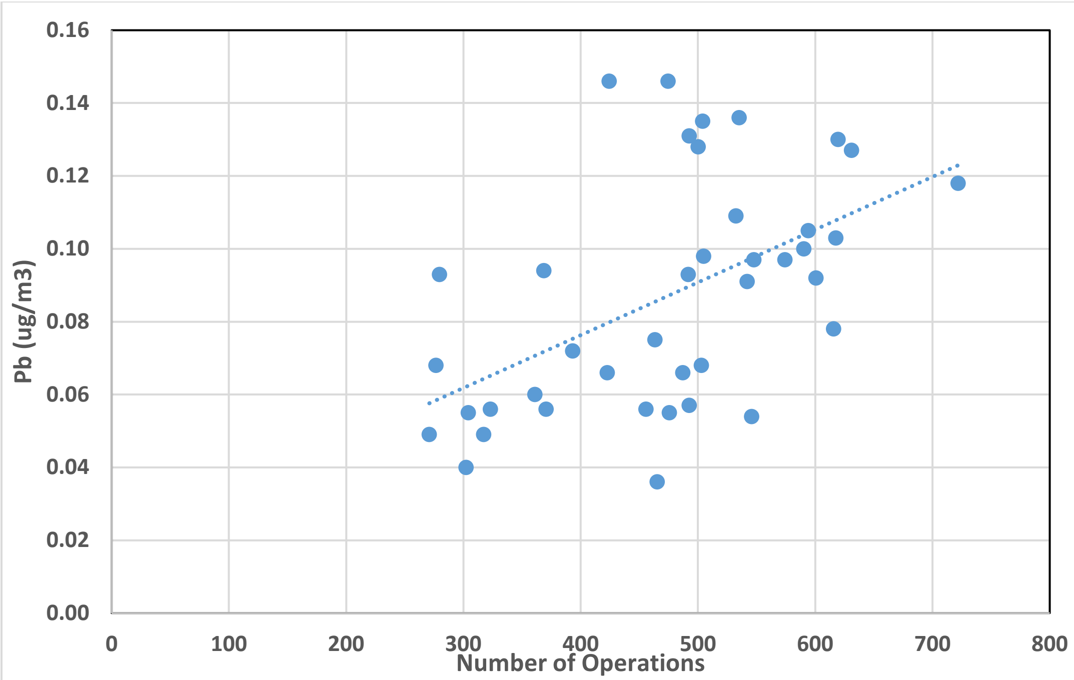

Figure 4. Example of the relationship between monitored lead concentrations and piston-engine aircraft activity.[50]

Specifically, based aircraft data (i.e., the number and class of aircraft that are parked at an airport) were collected for airports included in this airport-specific activity analysis. Data from previous EPA studies at six airports showed agreement within 10% between the number of SE and ME aircraft based at an airport and onsite observations of piston-engine aircraft activity at the airport (see Appendix B for study details).[51] As such, the number and class of aircraft based at each airport included in this airport-specific activity analysis was used to refine the national average percentages for estimating the number of LTOs specific to piston-engine aircraft, and then SE versus ME piston aircraft.

For each airport included in this analysis, the number of aircraft based at that airport was collected from available data sources.[52] Next, for each airport, the percent of total operations

[50] The relationship between monitored lead concentrations and piston-engine aircraft activity is impacted by several parameters including distance of the monitor from the area where aircraft conduct run-up checks, wind speeds, the type of aircraft (multi-engine or single-engine), and the type of operation (full landing and take-off versus touch-and-go. This figure does not analyze each of these influencing variables but is illustrative of the general relationship between activity and lead concentration at a general aviation airport).

[51] SE and ME aircraft based at an airport were considered piston-engine aircraft. While some SE and ME aircraft based at an airport may be turboprop or other non-piston-engine aircraft, comparisons with onsite activity counts suggest based aircraft data provide reasonable, airport-specific data and FAA considers based aircraft data to be a reliable indicator of activity at small airports (FAA 2015).

[52] A search was conducted for airport master plans or onsite studies on piston-engine aircraft activity, and in the absence of such information, based aircraft data were used from airport master plans or Airnav.com.

conducted by piston-engine aircraft was calculated using the number of SE and ME aircraft over the total number of aircraft based at the airport (i.e., sum of SE and ME based aircraft over total SE, ME, turboprop, jet, and helicopter based aircraft multiplied by 100). Similarly, the percent of piston-engine operations conducted by SE versus ME aircraft was calculated using the numbers of SE versus ME aircraft based at the airport (e.g., SE based aircraft over sum of SE and ME based aircraft multiplied by 100). Table 3 presents a summary of the percent of LTOs allocated to piston-engine aircraft, and separately SE versus ME piston aircraft, in the national analysis compared to the allocation using data for aircraft based at the airports included in this airport-specific activity analysis.

Table 3. **Comparison of Piston-Engine Activity Estimates Using National Averages versus Airport-Specific Data**

	National Analysis National Averages	**Airport-Specific Based Aircraft Data[53]**	**Data Sources**
% piston versus jet operations	GA: 72% AT: 23%	Unique to each airport (%SE & ME based aircraft of total based aircraft) GA & AT Mean: 92% GA & AT Range: 60 – 100%	National Analysis: (FAA 2010, USEPA 2011) Airport-specific: Airport Master Plans & Airport Master Record Forms 5010-1 & 5010-2
% single-versus multi-engine operations	GA SE: 90% GA ME: 10% AT SE: 57% AT ME: 43%	Unique to each airport (%SE OR ME based aircraft of SE AND ME based aircraft) • GA & AT SE: o Mean: 89% o Range: 58 - 99% • GA & AT ME: o Mean: 11% o Range: 0.02 – 42%	National Analysis: (FAA 2010, USEPA 2011) Airport-specific: Airport Master Plans & Airport Master Record Forms 5010-1 & 5010-2

In general, for the airports evaluated here, using the number of piston-engine aircraft based at the airports as a surrogate for activity suggests that piston-engine aircraft activity at these airports is higher than indicated by the national average fraction (Table 3). The higher percent

[53] In the national analysis, the percent of activity attributed to piston-engine vs. jet, and separately, multi- vs. single-engine aircraft differed for GA vs. AT activity based on FAA data; however, based aircraft data do not provide information on differences between GA and AT and thus the same percentages are used for both.

of piston-engine aircraft activity at these airports is expected given that master plans and other available information (e.g., airport websites) show that these airports are predominately GA airports, which generally have higher levels of piston-engine aircraft activity compared to a national average that includes activity at commercial and other larger airports with more jet activity. For the percentage of piston-engine aircraft activity conducted by SE versus ME aircraft, the number of SE and ME aircraft based at these airports suggest similar percentages of aircraft activity are conducted by each aircraft class compared to the national average data for GA activity. Conversely, the number of ME aircraft based at these airports generally suggest ME activity is lower than the national average used to estimate ME piston aircraft activity from total AT activity (Table 3). The airport-specific activity estimates calculated using aircraft based at these airports were used to calculate refined model-extrapolated lead concentrations, per the methods described in Table 2. These refined model-extrapolated concentrations are compared with national analysis values, as well as relevant monitoring data, in Section 4.

3.3.3 Airport-Specific Criteria for Identifying Potential Lead Levels Above the NAAQS

This section summarizes the approach and rationale for selecting airports included in the airport-specific activity analysis of lead concentrations at the maximum impact area. At a high-level, this approach entails identifying airports where the maximum 3-month average model-extrapolated concentrations may be above or approach the NAAQS, characterizing model-extrapolated maximum 3-month concentrations at these airports using airport-specific, refined estimates of aircraft activity splits, and then evaluating each airport on local criteria such as the proximity of the maximum-impact site to unrestricted public access. The detailed methods for this analysis are provided in Table 4.

Table 4. **Steps for Identifying Airports Where Lead Concentrations May Be Above the Lead NAAQS**

Step #	Step	Description	Rationale	Data Source
Steps 1 – 3 Objective: Identify a subset of airports where, considering sources of variability and uncertainty, model-extrapolated atmospheric lead concentrations could be above or approach the NAAQS for Lead.				
1	**Identify airports with maximum model-extrapolated concentrations approaching or above the NAAQS**	Sum the contributions of single- and multi-engine T&G and LTO operations to atmospheric lead concentrations at the maximum impact site for the maximum activity period from the national analysis described in Section 3.2. Identify all airports where the maximum concentration is above or is within 10% of 0.15 µg/m^3.[54]	The primary and secondary National Ambient Air Quality Standards for Lead are 0.15 micrograms per cubic meter lead in total suspended particles as a 3-month average. Because the AQFs relate operations to average atmospheric lead concentrations over the same timescale (3 months), the results of the national analysis indicate whether or not model-extrapolated lead concentrations may approach or be above the concentrations specified in the NAAQS for lead when the inputs described in Section 3.2 are used.	National Analysis Step 14 and 40 CFR Part 50
2	**Identify airports with maximum model-extrapolated concentrations approaching or above the NAAQS when all GA and half of all AT operations are assumed to be**	Scale the contributions of single- and multi-engine T&G and LTO operations to maximum impact area atmospheric lead concentrations to characterize these concentrations if 100% GA operations and 50% of AT operations were operated by piston-engine aircraft.	As detailed in Steps 1a and 1b in the national analysis methods, the national analysis assumed that 72% of GA and 23% of AT operations are performed by piston-engine aircraft. The current step identifies airports where concentrations would be above or approach the NAAQS if piston-engine aircraft were a larger portion of activity at each airport.	National Analysis Steps 1a and 1b and GAATA Survey

[54] Aircraft activity for the most recent year available was evaluated at this stage; airports where overall activity decreased such that estimated lead concentrations were no longer within 10% of 0.15 µg/m^3 were excluded.

Step #	Step	Description	Rationale	Data Source
	piston aircraft operations			
2a	Scale concentration contributions from T&G operations	Scale lead concentration contributions from GA operations by (1/0.72)	In the national analysis, all T&G operations are assumed to be from GA flight activity. Thus, as concentrations scale with operations, both single- and multi-engine concentrations can be scaled by the proportional change in GA piston-engine operations.	
2b	Scale concentration contributions from full flight operations	Scale full flight lead concentration contributions from AT operations by (0.5/0.23), the ratio of new operational cycles to old operational cycles for both SE and ME concentration contributions.	Both GA and AT operate SE and ME full flight operations.	National Analysis (FAA 2010, EPA 2011)
3	**Identify airports with maximum model-extrapolated concentrations approaching or above the NAAQS when at least 20% of operations occur at the most-used runway end during the maximum 3-month period**	Scale model-extrapolated lead concentrations by the ratio (0.2/X), where X is the airport-specific fraction of operations occurring at the most-used runway end during the maximum 3-month period and X < 0.2.	For the airports that are identified as potentially having lead concentrations approaching or above the NAAQs for lead at Step 1 of the airport specific analysis, the average percentage of operations occurring at the maximum period runway end is 20%. This sensitivity analysis identifies airports where operations at the most-used runway end may have been underestimated due to assumptions about wind direction, runway assignment, and local seasonal operational profile.	Airport Specific Analysis Step 1
Result: Identification of a subset of airports as having model-extrapolated lead concentrations that could be above the NAAQS for lead.				
Steps 4 – 7 Objective: Refine model-extrapolated concentrations at the subset of airports identified in Steps 1-3 using airport-specific activity data				
4	**Collect based-aircraft data for the**	Designate to each airport in the airport-specific analysis counts of jet, single-	For the national analysis, national average splits of piston/non-piston and subsequently	FAA Form 5010 Data

Step #	Step	Description	Rationale	Data Source
	subset of airports identified in Steps 1-3	engine, and multi-engine aircraft from reported based-aircraft numbers at that airport.	SE/ME operations were applied to both GA and AT operations. Because individual airports may serve different aircraft populations, an airport-specific activity assessment may provide a refined characterization of operational splits by aircraft type. This assessment uses counts of aircraft based at a particular airport as a proxy for a representative sample of the split of operations by aircraft type.	
4b	Retain national average splits of operational cycles for airports with no based-aircraft data in Form 5010.	Where airports have no reported based-aircraft data[55], retain the national average splits of operational cycles by SE/ME and Full/T&G for AT and GA.	Where based-aircraft are not reported, the national average percentage of SE/ME and Full/T&G operational cycles remain the best estimates of operational characteristics at that individual airport.	National Analysis (FAA 2010, EPA 2011)
4c	Retain national average splits of operational cycles for airports with low based-aircraft counts relative to annual operations.	Where airports have an annual-operations-to-based-aircraft ratio greater than 730[56], retain the national average splits of operational cycles by SE/ME and Full/T&G for AT and GA.	As based-aircraft numbers are self-reported, Form 5010 Data may be incomplete at some airports. Further, at busy airports with significant commercial or AT traffic, aircraft based at the airport may not be representative of all aircraft serving the airport. The lower the ratio of operations-to-based-aircraft, the more appropriate based-aircraft is expected to be a proxy for operational splits. We make the assumption that annual operations-to-based aircraft greater than 730 (2 operations per based aircraft per day), is an upper limit above	

[55] For the airport-specific analysis presented in Section 4, 5.7% of airports have no based-aircraft data.

[56] For the airport-specific analysis presented in Section 4, 10.0% of airports have annual-operations-to-based-aircraft ratios above 730.

Step #	Step	Description	Rationale	Data Source
			which the based aircraft data are not a suitable proxy for activity at an individual airport.	
5	**Assign splits of GA and AT piston/non-piston operations from based-aircraft data**	Characterize the number of operations that would be performed by piston-engine aircraft at each airport if the non-jet aircraft based at the airport were representative of the percent of GA and AT operations performed by piston-engine aircraft at that airport.	While several data sources provide airport-specific aircraft activity data (separately for General Aviation (GA) and Air Taxi (AT) activity), none specifically identify the number of *piston-engine* aircraft LTOs that occur at each U.S. airport. In the national analysis, a default percentage representative of national averages was used to determine piston-engine aircraft operations at each airport; this analysis uses local airport-specific information (namely based-aircraft) to better characterize model-extrapolated lead concentrations at those airports that could have model-extrapolated concentrations that approach, or be above the NAAQS for lead as identified in Steps 1-3.	FAA Form 5010 Data
6	**Assign splits of ME and SE Full and T&G operations from based-aircraft data**	Characterize the percentage of piston aircraft operations that would be classified as SE Full, SE T&G, ME Full, and ME T&G	In the national analysis, default percentages of operational splits for AT and GA operations by aircraft class (SE/ME) and operational cycle type (Full/T&G) representative of national averages were used to characterize piston aircraft operations at each airport; this analysis uses local airport-specific information (namely based-aircraft) to better characterize model-extrapolated lead concentrations at those airports that could have model-extrapolated concentrations that approach, or are above the NAAQS for lead as identified in Steps 1-3.	FAA Form 5010 Data

Step #	Step	Description	Rationale	Data Source
6a	Determine operational splits for AT at each airport	The percent of AT operational cycles that are SE (or ME) full LTO matches the percent of based-aircraft that are SE (or ME).	All AT operations are considered to be full LTOs.	
6b	Determine operational splits for GA at each airport	The percent of GA operational cycles that are SE (ME) matches the percent of based-aircraft that are SE (ME). Of the GA SE operational cycles, 24% are characterized as T&G consistent with the national analysis. Of the GA ME operational cycles, 20% are characterized as T&G consistent with the national analysis.	Both full LTO and T&G operational cycles are performed by GA aircraft.	
Result: Characterization of a refined estimate of the number and type of operations performed by SE and ME piston-engine aircraft for each of the airports identified in Steps 1-3.				
7	**Refine model-extrapolated lead concentrations using updated operational splits**	For the airports identified in Steps 1-3, estimate model-extrapolated lead concentrations at and downwind of the maximum impact site using the data gathered in Steps 4 – 6 paired with the methodology described in the National Analysis (Table 2).		National Analysis Steps 3-14
Result: Lead concentration estimates at and downwind of the maximum impact site at the most active runway end during the most active 3-month period for each airport identified in Steps 1-3 using airport-specific activity data.				
Step 8 Objective: Identify whether there is unrestricted access to the area of maximum impact at airports identified at Step 7				
8	**Identify airports where there is unrestricted access to the 50 m perimeter around a**	For the airports that have model-extrapolated lead concentrations that are above the lead NAAQS as identified in Step 7, estimate the distance from the run-up area at the most-utilized	The layout and footprint of many general aviation airports is such that, aircraft run-up areas and the maximum impact site may be in close proximity to where people have unrestricted access. We sub-select airports	Satellite and street-view imagery

Step #	Step	Description	Rationale	Data Source
	maximum impact site	runway end to the nearest unrestricted access using satellite imagery.	where there was unrestricted access within 50m of the maximum impact site where lead concentrations were estimated as potentially above the lead NAAQS in Step 7.	
9	**Identify local airport characteristics that may influence lead concentrations at the maximum impact site**	For the airports that have model-extrapolated lead concentrations that are above the lead NAAQS as identified in Step 7, review satellite imagery and airport documentation to determine if there are any airport-specific conditions or characteristics that could influence lead concentrations at the maximum impact site.	As all airports are unique, any airport may have a layout, local characteristic, or operational pattern that may differ from the assumptions underlying the national analysis and may impact resulting atmospheric lead concentrations.	Satellite imagery, airport master plans
Result: Identification of airports that have model-extrapolated lead concentrations above the NAAQS for lead considering both airport-specific activity data and unrestricted access to the maximum impact area.				

3.4 Characterization of Uncertainty of Cross-Airport Parameters that Influence the Potential for Lead Concentrations to Be Above the NAAQS for Lead

As discussed in Section 1, the goal of this work is to characterize lead concentrations at and downwind of the maximum impact area at airports nationwide. The approach described in Sections 3.2 and 3.3 was selected because of the consistent set of ground-based parameters that are inherent to safe operation of piston-engine aircraft. Namely, that these aircraft take-off into the wind and conduct pre-flight engine checks adjacent to the take-off runway end. These parameters are consistent across airports, and thus constrain the uncertainty and variability that might be associated with results based on combining information from one model airport with activity estimates at airports nationwide. The limited set of key parameters, which influenced maximum impact area ground-level air lead concentrations in previous modeling by EPA and others, were: 1) the duration of run-up, where longer run-up times results in higher concentrations, 2) the concentration of lead in the fuel, where higher avgas lead concentrations results in higher concentrations, 3) activity, where more piston-engine aircraft activity increases lead concentrations, 4) the percent of activity conducted by ME piston-aircraft, where more ME activity results in higher lead concentrations due to the higher fuel consumption rates of these aircraft relative to SE aircraft, and 5) meteorological factors and local topography (including wind speed, wind direction, mixing height, atmospheric stability, and surface roughness) (Section 2; Appendix A) (Carr et al. 2011, Feinberg et al. 2016).

Parameters 3 and 4 (activity estimates and SE/ME aircraft splits) were evaluated for a subset of airports for which uncertainty in the extent to which national average fractions represented the individual airport would most influence whether or not model-extrapolated concentrations are above the lead NAAQS, as described in Section 3.3. The uncertainty from these two parameters and the fifth parameter (meteorological and other local factors) are additionally assessed qualitatively in Section 4.4.

The duration of run-up operations and the concentration of lead in avgas were both found to be highly influential in ground-level 3-month average lead concentrations in air attributable to piston-engine aircraft. Run-up emissions accounted for 82% of the 3-month average lead concentration attributable to piston-engine aircraft in EPA air quality modeling at a model facility, and was a primary contributor to emissions in modeling conducted by Feinberg et al. (Section 2, Appendix A) (Feinberg et al. 2016). Moreover, variation between the 5th and 95th percentiles of average run-up times observed in EPA modeling resulted in an almost 8-fold variation in concentration attributable to only run-up emissions (Appendix C). Similarly, Feinberg et al. found greater variation in the duration of run-up than that of other modes of operation in the LTO cycle (e.g., landing and take-off time in mode), and variation in run-up time led to variation in concentrations downwind (Feinberg et al. 2016).

Similarly, the concentration of lead in avgas has a direct impact on atmospheric lead concentrations attributable to piston-engine aircraft activity, where higher levels of lead in fuel result in greater lead emissions and hence concentrations of lead in air. The ASTM standard for the maximum lead concentration in 100LL was used in the national analysis; however, the amount of lead in the fuel can vary across fuel suppliers and by batch. The concentrations of lead in air attributable to aircraft are expected to directly scale with the concentration of lead in avgas; thus, the lead avgas concentration was used as a scalar in the calculation of model-extrapolated concentrations at airports nationwide (see Equation 2, Section 3.1). Based on the important influence of these two parameters (run-up time and avgas lead concentration) in modeling 3-month average lead concentrations attributable to piston-engine aircraft activity, additional information was gathered to further characterize each parameter in results from both national and airport-specific activity analyses.

Information on average run-up times was collected from a series of studies that observed run-up operations at five airports (Appendix C) (USEPA 2010a, Heiken et al. 2014).[57] The average run-up time from each airport was used to develop a distribution of average run-up times.[58] This distribution of run-up times provided a way to evaluate model-extrapolated lead concentrations based on observations at a larger number of airports compared to the run-up times used in the national analysis, which were based on observations at the model airport. The distribution of average run-up time across the five airports was lognormally distributed with an average of 70 seconds, compared to the 40- or 63-seconds used for SE or ME aircraft, respectively, in the national analysis (Table 5). The relationship between variation in run-up time and concentrations of lead in air at and downwind of the maximum impact area was not characterized in the additional studies used to develop the distributions of average run-up times, and thus observations at the model airport were used to characterize how changes in run-up time impacted changes in lead concentrations in the maximum impact area and downwind (See Appendix C for details).

The distribution of average run-up times combined with an understanding of the relationship between run-up time and downwind lead concentrations attributable to piston-engine aircraft provided the necessary inputs for conducting a Monte Carlo analysis. The objective of the Monte Carlo analysis was to characterize the impact of variation in the 3-month average run-up time at a given airport on 3-month average model-extrapolated lead concentrations. Conceptually, the Monte Carlo analysis entailed repeatedly selecting a run-up time value from the distribution of average run-up times, and then adjusting the model-extrapolated lead concentration based on the difference between the selected run-up time and the run-up time used in the national analysis. For example, if an average run-up time of 70 seconds was selected from the distribution of average run-up times, then the national model-extrapolated concentration for SE piston aircraft would be adjusted up to account for the 30 second difference between the time used in the national analysis (40 seconds) and the time selected in the Monte Carlo draw. The amount of increase in concentration in this example would be based

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[57] One airport was included in two different studies, so while four unique airports were included in the studies referenced here, a total of five observational periods is included in the combined dataset.
[58] The use of average run-up times was selected as more representative of run-up times over a 3-month period, the time period of the model-extrapolated concentrations, than the variability observed in the raw run-up time data. For consistency with the national analysis, the median, rather than mean, run-up time at RHV was retained in the distribution of run-up times across the five airports included here.

on the relationship observed between run-up time and concentration at each distance downwind at the model airport, such that the concentration of lead in air would increase more at the maximum impact site than locations downwind (see Table C-1 in Appendix C). The resulting model-extrapolated concentration at each location, which accounted for the change in run-up time, would then be used to adjust the model-extrapolated concentration resulting from the national analysis. The Monte Carlo analysis used 10,000 iterations (i.e., 10,000 average run-up times were selected from the distribution and used to adjust the model-extrapolated concentration at each airport, at each downwind distance, which produced 10,000 adjusted concentrations that then provided a range of potential concentrations at each airport, at each downwind distance, based on variation in run-up time).

A similar approach was used to characterize the impact of variation in avgas lead concentrations on 3-month average model-extrapolated atmospheric lead concentrations. Available data from FAA and EPA reporting lead concentrations in avgas samples had an average lead concentration of 1.79 g/gal and were normally distributed within the range specified for 100LL (i.e., 1.70 to 2.12 g/gal) (see Appendix C for details on avgas lead data and their distribution). A Monte Carlo analysis was used to characterize variation in 3-month average model-extrapolated lead concentrations based on variation in avgas lead concentration. As with run-up time, a value was selected from the distribution of avgas lead concentrations (Table 5), and then used to scale a model-extrapolated concentration. For example, if an avgas lead concentration of 1.80 was selected from the distribution, a model-extrapolated concentration would be scaled by 0.85 (i.e., 1.80/2.12) to decrease extrapolated concentration and account for a lower concentration of lead in fuel. The Monte Carlo analysis was conducted 10,000 times. Results of the avgas lead and run-up time Monte Carlo analyses were combined per Equation 3 to provide model-extrapolated concentrations that account for variation in each parameter at and downwind of the maximum impact area at each US airport (see Appendix C for details).

Eq. 3:

$$\text{Monte Carlo Adjusted Lead Concentration, } [Pb]_{MC} = L_{MC}/2.12\frac{\text{g Pb}}{\text{gal}}(Y_n \times C_n)$$

Where:

L_{MC}= concentration of lead in avgas (g/gal) from Monte Carlo analysis of avgas lead distribution
Y_n= model-extrapolated concentration from national analysis at location n
C_n= %difference change in concentration at location n due to change in run-up time (see Equation C-1)
N= location at or downwind of maximum impact (i.e., 0, 50, 100, 150, 200, 250, 300, 400, 500 meters)

Table 5. Monte Carlo analysis inputs for characterizing variability in key AQF parameters

Variable	National Analysis		Monte Carlo Analysis				Assumptions
	Data Source	Value	Data Source	Mean (SD)	Range	Distribution Shape	
Run-up Time (seconds)	Model facility (Appendix A)	SE: 40 ME: 63	(USEPA 2010a, Carr et al. 2011, Feinberg and Turner 2013)(Appendix A) (n=5)	SE & ME: 70 (21)[59]	Min: 49 Max: 91	Log-normal (Time in Mode)	We assume that the log-normal distribution of data from the five airports noted in text is representative of the distribution of piston aircraft run-up times nationwide since these are the only data in the literature reporting this information. We assume that bounding the distribution by one sigma above and below the logarithmic mean is representative of average run-up times over a 3-month period.
			Model Airport (Appendix A)			Exponential (distance)	The lead concentration attributable to run-up decreases as a negative power law with distance from the maximum impact site. As such, increases or decreases in run-up time compared to an average influences lead concentration more at 0 or 50 m from run-up than at 500 m meters for run-up. Our modeling suggests an exponential curve describes the relationship between run-up time and variability in lead concentration estimate (see Appendix C for details).
Avgas Lead Concentration (g/gal)	ASTM standard	2.12	EPA & FAA fuel samples (n=116)	1.79 (0.27)	Min: 1.70 Max: 2.12	Normal	We assume that the normal distribution of data from EPA and FAA fuel samples is representative of the distribution of avgas lead content at all US airports. The EPA fuel data were collected during modeling studies discussed in Section 2. FAA published a study reporting the lead concentration of avgas fuel samples which was also used in this analysis. We bounded the distribution based on the ASTM fuel specifications for 100 octane Very Low Lead avgas (100VLL) which has a lead concentration of 1.70 g/gal, and 100 Low Lead (100LL) which has a maximum lead concentration of 2.12 g/gal.

[59] As noted in the text, the average run-up times observed in four studies were used in combination with the median run-up time observed at the model airport, and used in the national analysis, to develop a distribution of average run-up times. As such, the standard deviation here is the SD of average values.

4. Model-Extrapolated Lead Concentrations: Results and Uncertainty Characterization

In this section we present results of the national analysis and the evaluation of individual airports with the potential to be above the lead NAAQS described in Sections 3.2 and 3.3, respectively, as well as the results of our methods to characterize uncertainty and variability in model-extrapolated concentrations of lead from piston-engine aircraft operating at US airports. Section 4.1 provides results of the national analysis; we then further evaluate of the impact of the wind speed, and, separately, multi-engine aircraft activity on lead concentrations at the maximum impact site. Lastly, Section 4.1 characterizes performance of the model-extrapolation methodology through a comparison of results to monitored concentrations. Section 4.2 provides results of using airport-specific data to refine concentration estimates at airports with the potential for lead concentrations to be above the lead NAAQS, and similarly characterizes performance through comparisons of results with monitored concentrations. Section 4.3 discusses the results of the quantitative uncertainty analysis on variability in run-up durations and avgas lead concentrations. Finally, Section 4.4 discusses qualitative uncertainty analyses for results from both national and airport-specific activity analyses.

4.1 Ranges of Lead Concentrations in Air at Airports Nationwide

The national analysis methods described in Section 3.2 produced estimates of 3-month average model-extrapolated lead concentrations at and downwind of maximum impact areas at 13,153 airports nationwide. These model-extrapolated concentrations are calculated for 3-month periods of peak activity at each airport, and are attributable only to piston-engine aircraft activity.[60] Recall that model-extrapolated concentrations should decrease with increasing distance from maximum impact area, based on the AQFs used in the analysis (Table 4), and that concentrations across all sites should generally correlate with estimates of piston-engine aircraft activity given the relationship between activity and concentration described in Section 3.3.2. Table 6 shows that indeed model-extrapolated concentrations decrease as distance from the maximum impact area increases (left to right in table), and higher levels of piston-engine activity (i.e., LTOs) generally correlate with higher model-extrapolated concentrations (top to bottom in table). The decrease in model-extrapolated concentrations with increasing distance from the maximum impact area has also been observed in lead monitoring data near airports servicing piston-engine aircraft (Environment Canada 2000, Fine et al. 2010, Anchorage DHHS 2012), as well as lead modeling work conducted by others (Feinberg et al. 2016), and conforms to near field concentration gradients for other primary pollutants.

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[60] As discussed in Section 2, since model-extrapolated lead concentrations are attributable to piston-engine aircraft activity only, these lead concentrations may not reflect the total lead concentration (i.e., local emissions other than aircraft as well as local background lead concentrations are not included in the estimates provided in Table 6).

Table 6. Ranges of Piston-Engine LTOs and 3-month model-extrapolated lead concentrations at and downwind of maximum impact areas at airports nationwide during 3-month peak activity[61,62]

LTOs	Model-Extrapolated Concentrations of Lead (µg/m^3) at and Downwind of the Maximum Impact Area								
	Max Site	50 m	100 m	150 m	200 m	250 m	300 m	400 m	500 m
3,616 - 26,816	0.155-0.475	0.038-0.116	0.018-0.054	0.013-0.040	0.011-0.032	0.009-0.027	0.006-0.019	0.005-0.014	0.003-0.010
2,579 - 8,814	0.100-0.154	0.024-0.038	0.011-0.018	0.008-0.013	0.007-0.011	0.006-0.009	0.004-0.006	0.003-0.005	0.002-0.003
1,783 - 5,728	0.075-0.100	0.018-0.025	0.009-0.012	0.006-0.009	0.005-0.007	0.004-0.006	0.003-0.004	0.002-0.003	0.0017-0.0023
1,275 - 4,302	0.050-0.075	0.012-0.018	0.006-0.009	0.004-0.006	0.003-0.005	0.003-0.004	0.002-0.003	0.0015-0.0023	0.0011-0.0017
160 - 2,889	0.0075-0.050	0.002-0.012	0.001-0.006	0.001-0.004	0.001-0.004	0.0004-0.003	0.0003-0.002	0.0002-0.0016	0.00002-0.001
<1 - 446	< 0.0075	≤ 0.002	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.0004	≤ 0.0003	≤ 0.0002	≤ 0.0002

The relationship between piston-engine aircraft activity and model-extrapolated concentrations is discussed further below; this relationship is influenced by a few key factors that include the fraction of SE and ME piston-engine aircraft, and wind speed at a given airport. Looking specifically at model-extrapolated concentrations at maximum impact areas, results show a range of <0.0075 to 0.475 µg/m^3 at airports nationwide, depending on aircraft activity levels (Table 6). Inspecting the ranges of activity and model-extrapolated concentrations reveals that there is a wide range of activity that could result in model-extrapolated concentrations above the lead NAAQS. The airports with comparatively higher lead concentrations and 3-month maximum activity levels between 3,616 and 26,816 LTOs represent a mix of airports, some of which are dominated by SE aircraft activity and some of which have a mix of SE and ME aircraft activity. As noted earlier, SE activity results in lower lead concentrations per LTO compared with ME activity. Figure 5 presents a plot of the relationship between 3-month average concentrations and activity, with the relative amount of ME depicted in shades of blue. As indicated in Figure 5, more activity occurs at an airport dominated by SE aircraft to result in lead concentrations similar to those at other facilities where there is a mix of ME and SE aircraft. The mix of SE and ME activity, along with other characteristics of airports with model-extrapolated concentrations above the lead NAAQS is explored further in Section 4.2.

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[61] As discussed in Section 3.2, model-extrapolated concentrations in Table 6 are attributable to piston-engine aircraft activity and do not include local background lead concentrations.

[62] In monitoring 3-month average lead concentrations at airports, concentrations in µg/m^3 are typically presented out to two decimal places. Additional decimal places and/or significant figures are shown in this table and in select other figures either to demonstrate the trend of lead concentrations further downwind of the maximum impact location or at airports with few operations.

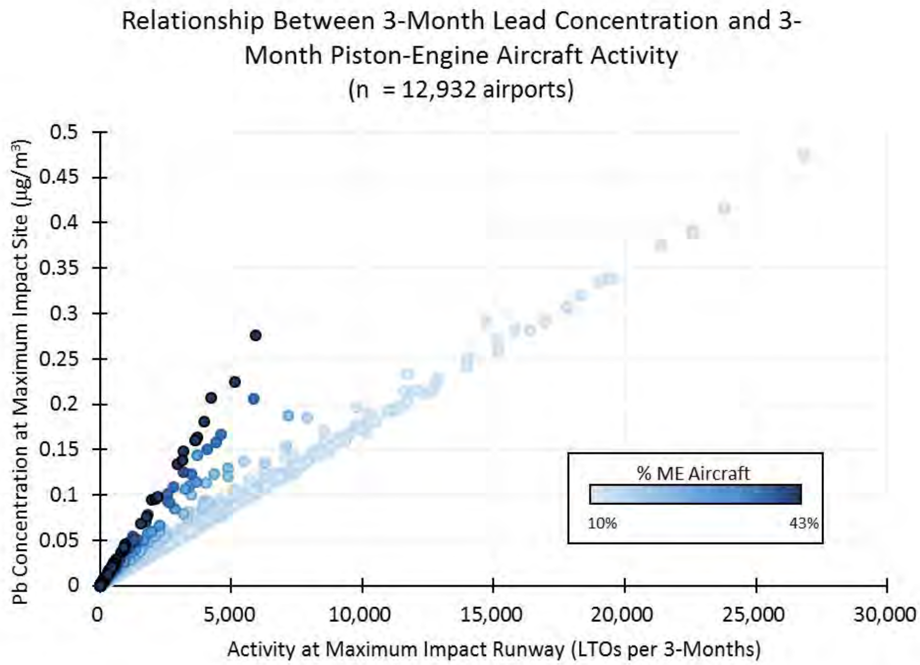


***Figure 5. The relationship between 3-month average lead concentration at the maximum impact site and piston-engine aircraft activity during the same 3-months. Blue shading denotes the relative amount of multi-piston-engine aircraft activity at each airport. Air Taxi data were used to estimate the relative ME aircraft activity at each airport since this type of activity is generally dominated by ME and data specific to multi-piston-engine aircraft activity is not available across US airports. Airports with zero LTOs (n = 221) were excluded from the figure for clarity*. This figure presents non-wind-adjusted concentrations using national default analysis parameters as described in Table 2 to better highlight the impact of multi-engine activity on concentration.**

As described in Section 3.2 and Table 2, wind speed at each airport relative to wind speed at the model airport can also influence model-extrapolated lead concentrations, and thus the maximum impact site concentrations were adjusted to reflect wind speeds at each airport. Airports with wind speeds during the 3-months of maximum activity that are higher than wind speeds measured at the model airport will have wind-adjusted concentrations that are lower than the non-adjusted concentrations using national defaults. Similarly, airports with lower wind speeds than the model airport will, in general, have higher wind-adjusted concentrations. Results of the wind-speed adjusted lead concentrations are compared with unadjusted values in Figure 6.

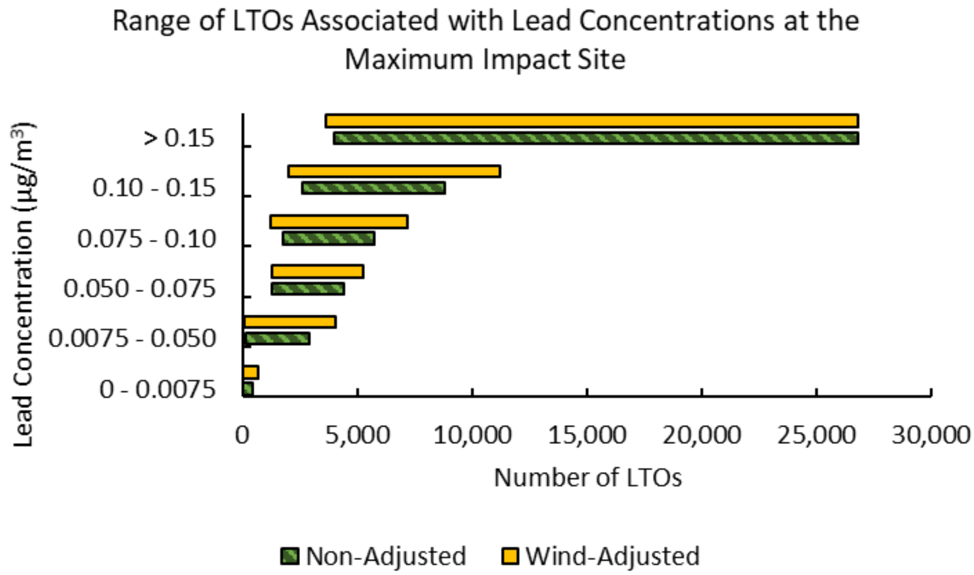


Figure 6. Average 3-month model-extrapolated concentrations versus the number of piston-engine LTOs during the same 3-month period at the maximum impact area runway end. Concentrations are generally categorized relative to the lead NAAQS (e.g., greater than the standard of 0.15 µg/m³, less than half the standard, 0.075 µg/m³, less than concentrations generally detected by monitors, 0.0075 µg/m³, etc).

Across all airports, the effect of the wind adjustment ranges from a 45% decrease in concentration to a 210% increase in concentration; however, 48% of airports have concentrations that change by less than 10%. The impact of the wind adjustment on maximum impact site concentrations for all airports is shown in Figure 7. In absolute difference, the 3-month maximum concentration at the maximum impact site changes by less than 0.01 µg/m³ at most airports. At airports with concentrations greater than half the lead NAAQS, the absolute concentration change from wind adjustment tends to be higher, from -0.06 to 0.16 µg/m³, as shown in Figure 8. Overall, results of adjusting for wind speed show that while this parameter is influential at individual airports, it does not meaningfully impact the range of concentrations in the maximum impact area at airports nationwide. In turn, individual airports with the potential to have concentrations above the lead NAAQS are evaluated more closely in Section 4.2.

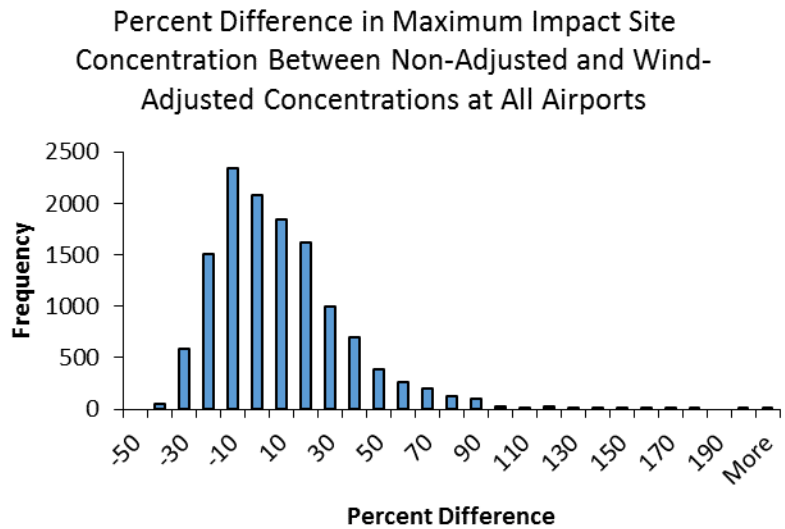


Figure 7. The percent change in 3-month maximum concentration at the maximum impact site from accounting for average inverse wind speed at all airports.

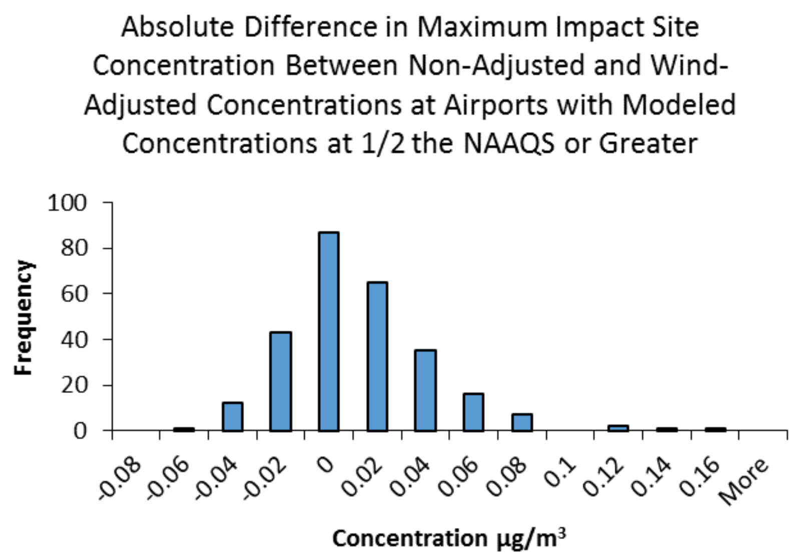


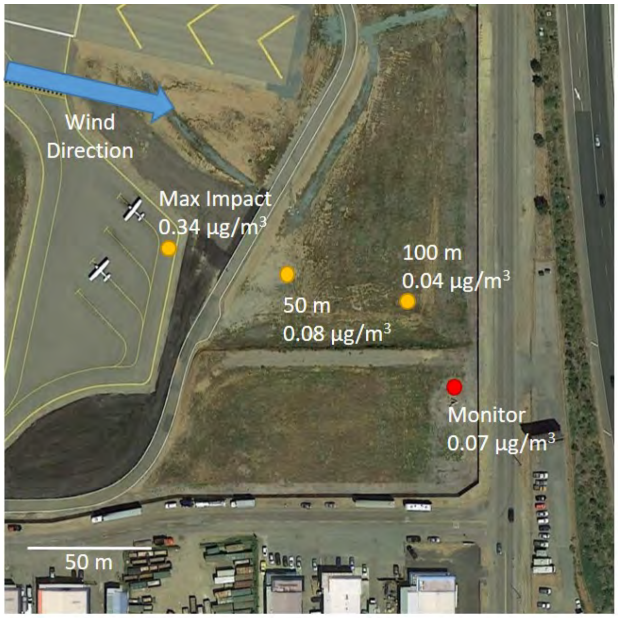
Figure 8. The absolute change in 3-month maximum concentration at the maximum impact site from accounting for average inverse wind speed at airports with concentrations greater than ½ the NAAQS for Lead.

The model-extrapolated concentrations from the national analysis presented above can be evaluated through a comparison to monitored concentrations. Such an evaluation would ideally be informed by monitored data that corresponds spatially and temporally with the model-extrapolated concentrations. However, as detailed below, monitored lead concentrations are only available at a subset of airports and none of these data are spatially and temporally consistent with model-extrapolated data. Nevertheless, a coarse comparison of model-extrapolated to monitored concentrations is feasible for a subset of airports at which monitors were placed proximate to the maximum impact area, or downwind, as part of evaluating attainment of the lead NAAQS.[63] In evaluating these comparisons, it is noteworthy that in addition to spatial differences, monitored and model-extrapolated concentrations differ in temporal periods and scope. Model-extrapolated concentrations were calculated for 2011 while monitored concentrations were collected over different 1-year periods depending on the airport.[64] As described in Section 3.1, while 2011 is expected to be generally representative of piston-engine aircraft activity during monitored periods, differences in the volume and type of piston-engine activity (i.e., SE vs. ME, full LTO vs. T&G) and meteorological conditions would be expected to impact the comparisons presented here. In addition, model-extrapolated concentrations are specific to aircraft lead emissions, while monitored concentrations include background lead from other sources. Other factors could influence lead concentrations in air from year-to-year as well, and both monitored, and model-extrapolated concentrations also have inherent variability and uncertainty. With the characteristics of each dataset in mind, Figure 9 provides a coarse comparison of national model-extrapolated to monitored concentrations at three airports with monitors placed proximate to the maximum impact area or downwind locations.[65] Each panel presents the monitored NAAQS design value (i.e., maximum 3-month average concentration during monitored time period) along with model-extrapolated concentrations. Across these airports, model-extrapolated and monitored concentrations generally align when considering both the downwind gradient, and horizontal transport of lead emissions at the maximum impact area.

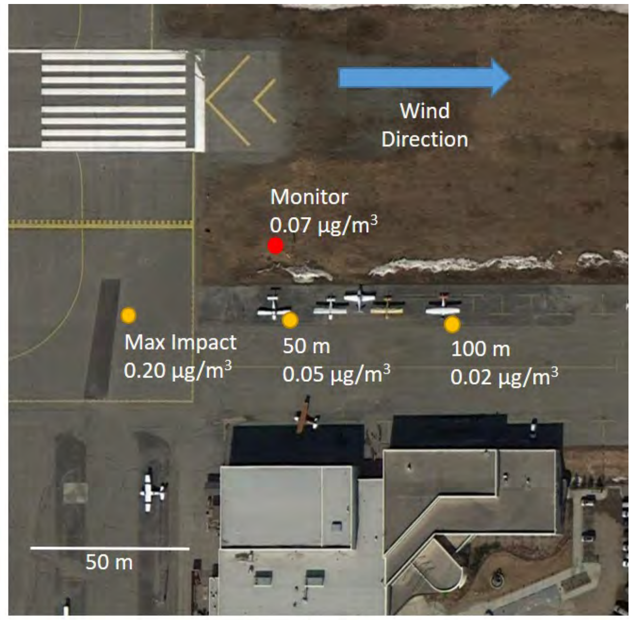
[63] Logistical considerations (e.g., aviation safety clearance regulations for siting fixed objects near the landing and take-off area, and availability of power in these locations) typically prevented placement of lead monitors in the maximum impact area.

[64] Monitoring agencies were required to measure the maximum lead concentration in ambient air resulting from specific lead sources, including a subset of airports USEPA (2010b). Revisions to Lead Ambient Air Monitoring Requirements.; these monitoring data are part of the lead surveillance network that is used to evaluate attainment of the NAAQS for lead (https://www3.epa.gov/ttnamti1/pb-monitoring.html). A summary of monitored data is available on the EPA website USEPA. (2017a). "Airport Lead Monitoring and Modeling." 2017, from https://www.epa.gov/regulations-emissions-vehicles-and-engines/airport-lead-inventories-air-quality-monitoring-air.

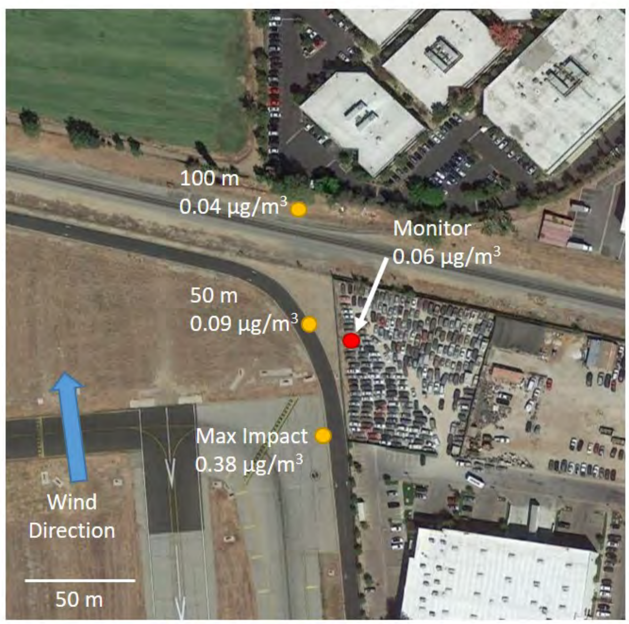
[65] Among the 17 airports where lead surveillance monitoring was conducted, eight NAAQS monitors were sited in locations proximate to or downwind of the maximum impact area. Four are presented in this section with the remaining four presented in Section 4.3. In two instances NAAQS monitors were sited particularly close to model-extrapolated locations, which supported an extended comparison of monitored to model-extrapolated concentrations, also in Section 4.3.



Airport A



Airport B



Airport C

Satellite Image Source: Google Earth

Figure 9. Coarse comparison of monitored to model-extrapolated lead concentrations at airports with NAAQS monitors sited proximate to the maximum impact area or locations downwind. Red dots represent approximate monitor placement, while yellow dots represent approximate locations of model-extrapolated concentrations from national analysis methods (Section 3.2). Blue arrows denote the prevailing wind direction at each airport. As noted above, the year in which monitored concentrations were collected varies by airport, while model-extrapolated concentrations represent 2011. All locations are based on scientific judgment of the alignment of model-extrapolated locations

from the expected maximum impact area. The max impact concentrations represented in the figure are not wind speed adjusted. The wind speed adjusted concentrations at max impact for airports A, B, C are 0.36, 0.23, and 0.44 µg/m^3 respectively.

4.2 Airports with Potential Lead Concentrations Above the Lead NAAQS with Unrestricted Access Within 50 m of the Maximum Impact Site

As described in Section 3.3, a series of sensitivity tests were performed to identify a subset of airports beyond those identified in the national analysis where model-extrapolated lead concentration estimates were above the NAAQS for lead. Additional data were then identified to calculate airport-specific activity estimates for each airport in this subset.[66] Next, the airport-specific activity estimates for each airport were used to calculate updated model-extrapolated lead concentrations for that airport with a focus on concentrations in the maximum impact area. In addition, for each of these airports, satellite imagery was utilized to assess if there was unrestricted access within 50 meters of the maximum impact site. The results of this screening analysis are presented in Table 7.

Each column in Table 7 represents the outcome of analysis steps presented in Section 3.3 and described in Table 4: the first column identifies the airport, the second column indicates the lead concentration at the maximum impact site relative to the lead NAAQS using national default parameters (Section 3.2); the third column adjusts the national default concentrations based on average inverse wind speed (Section 3.2); the fourth and fifth columns present the outcomes of airport-specific parameters that influence the potential for lead concentrations to be above the NAAQS for lead; the sixth column shows the results of the airport-specific-activity analysis before adjusting for average inverse wind speed; and the seventh column shows the results using both airport-specific activity and airport-specific wind speed data. Black filled circles indicate model-extrapolated concentrations are above the NAAQS for lead and white unfilled circles indicate model-extrapolate concentrations that are more than 10% below the NAAQS for lead. The potential impacts of additional local characteristics (e.g., mixing height, local terrain) on airport-specific estimates of lead concentration are discussed qualitatively in Section 4.4.

[66] As described in Section 3.3, airport-specific data consist of the number of SE and ME piston-engine aircraft based at an airport. Airport-specific activity estimates were calculated using the following steps. First, the number of LTOs specific to piston-engine aircraft was estimated by summing the number of SE and ME piston-engine aircraft based at an airport and dividing the sum by the total number of aircraft based at an airport, then multiplying the fraction by total LTOs at the airport. Next, the fraction of piston-engine aircraft LTOs conducted by SE piston aircraft was calculated by dividing the number of SE based aircraft by the total number of SE and ME based aircraft at an airport. The same approach was used to calculate the fraction of piston-engine aircraft LTOs conducted by ME piston aircraft. For airports where no based aircraft data were available or for where based aircraft numbers represented fewer than one aircraft for every 730 operations, national default splits were used for the airport-specific activity estimates.

Among the airports in Table 7, air quality monitoring has been conducted at RHV at a location approximately 60 m downwind from the maximum impact site. Lead concentrations at RHV measured 60 m downwind were above half the level of the lead NAAQS.[67]

Table 7. **Airports with Model-Extrapolated Lead Concentrations Potentially Above the Lead NAAQS at the Maximum Impact Area With Unrestricted Areas Within 50 Meters.**

Airports[68]	National Defaults	Wind Adjusted	% Piston Adjusted	Runway Shift	Based Aircraft	Based Aircraft Wind Adj.
52F	●	●	●	●	●	●
RHV	●	●	●	●	●	●
ORS	○	●	●	○	●	●
WHP	○	○	●	○	●	●

For the airports identified in Table 7, model-extrapolated concentrations increase when using airport-specific data to estimate piston-engine aircraft activity; the magnitude of the increase varies based on the difference between the airport-specific fleet and operational characteristics compared with the national average values used for piston-engine aircraft activity. The percentage of piston-engine activity estimated as SE versus ME also influences the magnitude of change between airport-specific and national analysis results. As described previously and in greater detail in Section B.4, the use of based aircraft to estimate piston activity, as well as SE and ME splits in activity was evaluated by comparing on-site observations with based aircraft at a subset of airports and reasonable agreement was observed (within 10%) between based aircraft and on-site observations. Additional factors that influence model-extrapolated concentrations (e.g., run-up time, avgas lead concentration) are discussed in Section 4.3. Figure 10 presents the model-extrapolated lead concentrations in the maximum impact area from both the airport-specific analysis and the national analysis at individual airports where lead concentrations at the maximum impact site with unrestricted access may potentially be above the lead NAAQS.

[67] See the program overview titled Airport Lead Monitoring: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100LJDW.PDF?Dockey=P100LJDW.PDF

[68] Airport codes are commonly used to identify airports; the name and location of airports in this table is provided in Appendix B.

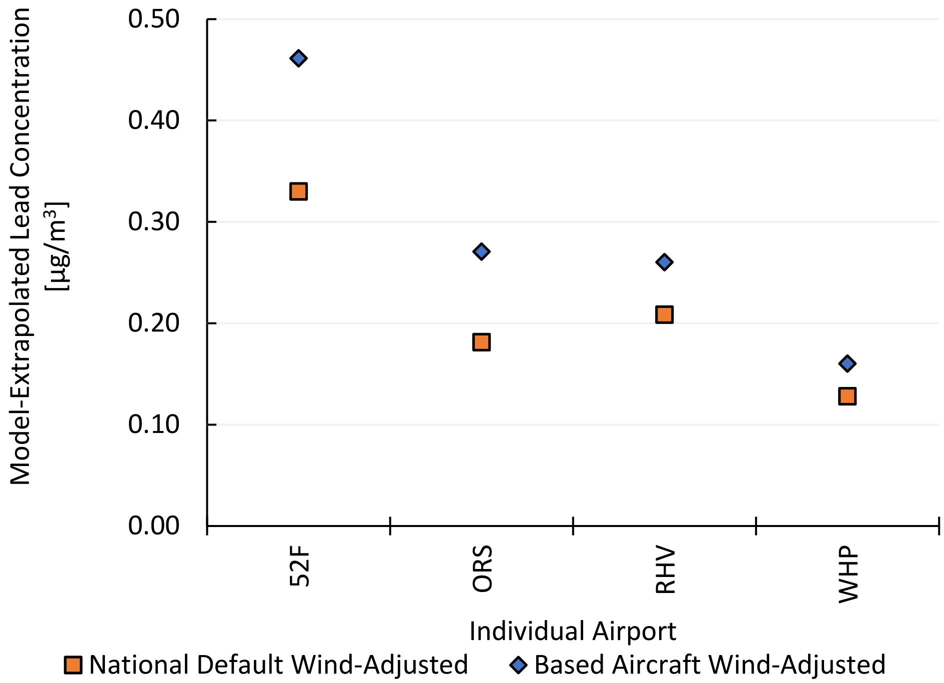
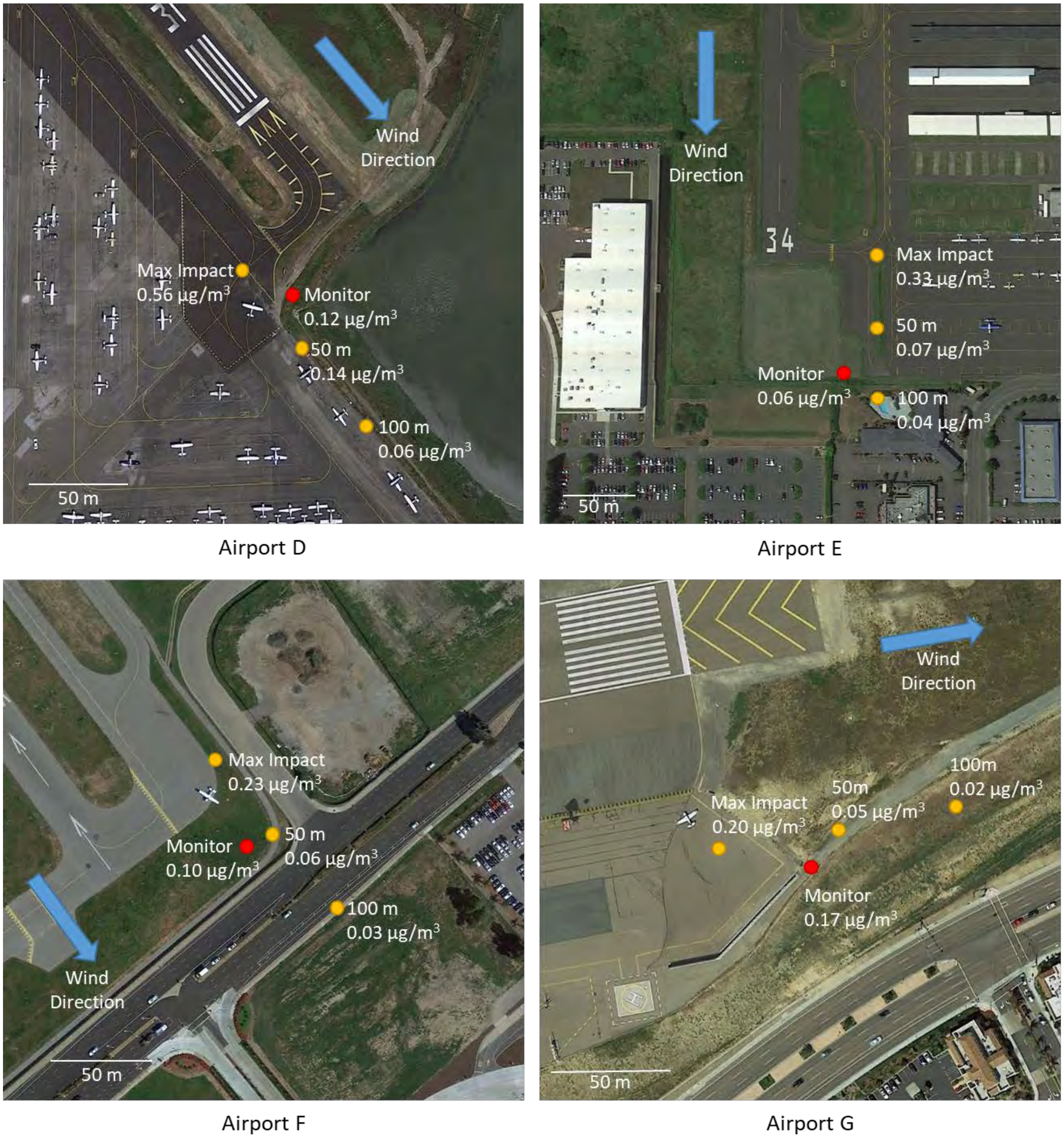


Figure 10. Comparison of model-extrapolated lead concentrations from the wind-speed adjusted national default parameters (orange squares; Section 3.2), and wind-speed adjusted airport-specific activity analysis (blue diamonds; Section 3.3) at airports that have the potential for maximum impact site concentrations to be above the NAAQS for lead with unrestricted access.

Similar to national analysis results, results of the airport-specific activity analysis can be evaluated through a comparison to monitored data. Of the airports included in the airport-specific activity analysis, four had NAAQS surveillance monitors located proximate to or downwind from the maximum impact area. Figure 11 presents the comparison of monitored and model-extrapolated concentrations at these airports. As discussed in Sections 3.4 and 4.1, the coarse comparison presented in Figure 11 has attendant uncertainties (e.g., spatial and temporal differences between monitor and model-extrapolated data). Despite these uncertainties, monitored data suggest that model-extrapolated concentrations which use airport-specific activity estimates generally align with monitored concentrations. A more in-depth comparison of model-extrapolated to monitored concentrations is presented in the context of additional uncertainty analysis in Section 4.4.



Satellite Image Source: Google Earth

Figure 11. Coarse comparison of monitored to model-extrapolated airport-specific lead concentrations at airports with NAAQS monitors sited proximate to the maximum impact area or locations downwind. *Red dots represent monitor location, while yellow dots represent approximate locations of model-extrapolated concentrations from airport-specific activity analysis (Section 3.3). Blue arrows denote the prevailing wind direction at each airport. Locations for model-extrapolated lead concentrations depicted here were based on approximated location of the dominant run-up location. The max impact concentrations represented in the figure are not wind speed adjusted. The wind speed adjusted concentrations at max impact for airports D, E, F, and G are 0.58, 0.31, 0.26, and 0.24 µg/m^3 respectively.*

4.3 Quantitative Uncertainty Analysis of Concentrations of Lead in Air at Airports: The Influence of Run-up Time and Avgas Lead Concentration

As with any analysis of this scope in which estimates of pollutant concentrations at facilities nationwide are developed using an extrapolation approach, there is inherent uncertainty and variability in the estimates. The focus here is on two key parameters that have been demonstrated in previous studies to impact lead concentrations at and downwind from the maximum impact area at airports: run-up time and avgas lead concentration. Run-up time and avgas lead concentrations are not constrained by the functional role of a given airport, but rather vary across airports independently of airport attributes. These two parameters were thus the focus of a quantitative variability evaluation using a Monte Carlo analysis, which is discussed in Section 3.4 above. Additional meteorological and local considerations may contribute to uncertainty at individual airports; the uncertainty from these parameters is discussed qualitatively in Section 4.4.

4.3.1 National Analysis and Airport-Specific Monte Carlo Results

Figure 12 shows the national analysis results with Monte Carlo bounds around each model-extrapolated concentration for the airport with the highest, and, separately, the airport with the lowest model-extrapolated concentration at the maximum impact site and downwind locations. As the Monte Carlo bounds show, variability in run-up duration and avgas lead concentrations add uncertainty to the exact range of model-extrapolated concentrations nationwide (i.e. exact value of the highest and lowest model-extrapolated concentration in the maximum impact area and downwind locations of US airports); however, the quantitative uncertainty shown in the Monte Carlo is small enough such that it does not obscure meaningful differences between model-extrapolated concentrations at different US airports.

Further, Monte Carlo results consistently show the potential for higher model-extrapolated concentrations than the national analysis results (compare black or blue dots to upper error bars in Figure 12). The potential for higher model-extrapolated concentrations is due to the difference in observed run-up times at the model airport compared to run-up times observed at airports included in the Monte Carlo analysis. As noted in Section 3.4 the deterministic national analysis used 3-month median run-up times for SE and ME, separately, which were measured at the model airport at which AQFs were developed, while the Monte Carlo analysis included observations of longer run-up times from studies at additional airports (Table 5). The increase in model-extrapolated concentrations due to the potential for longer durations of run-up at airports nationwide compared to that observed at the model airport, generally aligns with a sensitivity analysis conducted at the model airport. The sensitivity analysis showed that increasing run-up time from the 5th (16 seconds) to 95th (121 and 160 seconds for SE and ME respectively) percentiles resulted in approximately an order of magnitude increase in 3-month average modeled concentrations (i.e., 5th to 95th percentiles of 3-month average modeled concentrations increased from 0.043 to 0.322 µg/m^3 and from 0.005 to 0.035 µg/m^3 for SE and ME, respectively) (Appendices A and C). The average run-up time at a given airport may be impacted by a number of factors (e.g., the number of pilots in training); however, the use of average run-up time from airports with available data provides relevant information to characterize the potential range of concentrations at airports nationwide in a manner consistent with the approach laid out in Section 3.

While the concentration of lead in avgas is also included in the Monte Carlo analysis, this parameter influences results less than run-up duration for two reasons. First, the range of lead in avgas is smaller than the range of average run-up times used in the analysis (Table 5). Second, the impact of longer run-up durations is additive, whereas the impact of lower avgas lead concentrations is incremental (i.e., each additional second of run-up compared to the median value used in the national analysis contributes the same amount to downwind lead concentrations, whereas fuel with 2.10 g/gal lead rather than the 2.12 g/gal contributes 0.02 g/gal less to emissions). The difference in the influence of these parameters helps explain why the uncertainty analysis for model-extrapolated concentrations consistently demonstrates higher values compared with the point estimate.

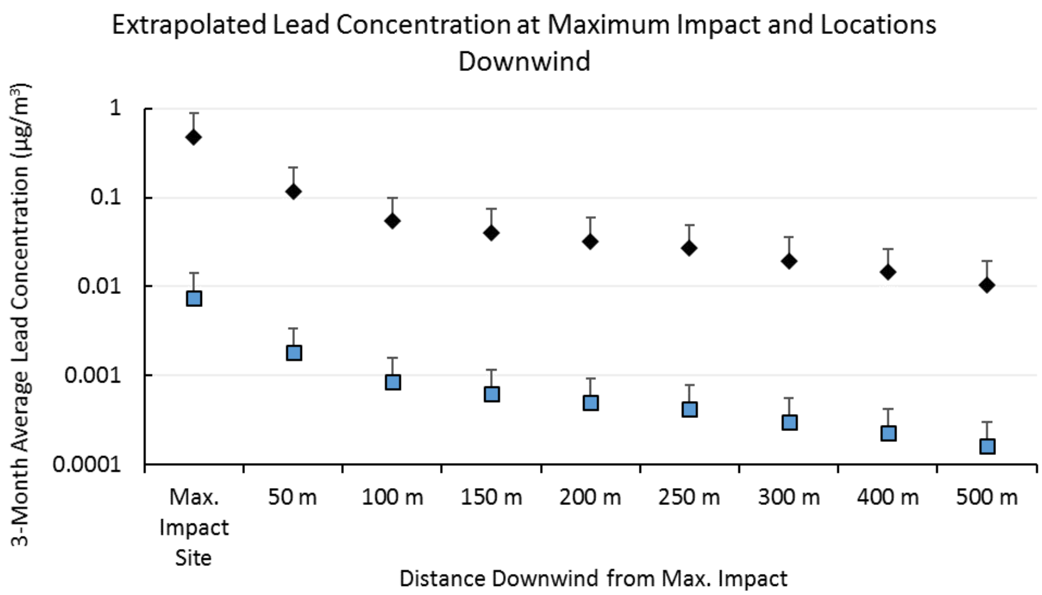


Figure 12. The range of model-extrapolated lead concentrations at and downwnind of the maximum impact area based on national analysis results. Black diamonds represent the maximum and blue squares represent the minimum model-extrapolated concentration at each location for the 13,153 airports included in the national analysis. Error bars are the concentrations at the 97.5th percentile of Monte Carlo results, which account for potential ranges in run-up time and avgas lead concentrations across airports.

Similar to the Monte Carlo bounds around national analysis results, the model-extrapolated concentrations from the airport-specific activity analysis are consistently at or near the 2.5th percentile of the Monte Carlo bounds while the 50th percentiles and 97.5th percentiles of the Monte Carlo analysis are on average 38% and 91% higher than the model-extrapolated concentrations from the airport-specific activity analysis. As discussed above, this observation is primarily the result of having used a shorter run-up time in developing the model-extrapolated lead concentrations in the national analysis compared with run-up times that have been observed at other airports, which were used in the Monte Carlo analysis (Table 5). In addition, the greater influence of run-up time versus lead concentrations in avgas on ground-based atmospheric lead concentrations, leads to changes in run-up time dominating the potential range of concentrations observed in the Monte Carlo results (ICF 2014, Feinberg et al. 2016). The uncertainty results presented here are sensitive to the choice of input distributions for avgas lead concentration and run-up time.

4.3.2 Comparison of Model-Extrapolated Concentrations From the Airport-Specific Activity Analysis with Monte Carlo Bounds to Monitored Concentrations in the Maximum Impact Area

To evaluate the approach for calculating airport-specific model-extrapolated concentrations with Monte Carlo bounds, results from the approach were compared to relevant monitoring data. Comparisons between model-extrapolated and monitored lead concentrations are most informative when the model-extrapolated and monitor concentrations are in the same approximate location. Two airports had monitors located in close proximity to the location of the model-extrapolated concentrations; however, monitoring at each airport was conducted during different time periods than the time period of national analysis. Thus, model-extrapolated concentrations were adjusted to reflect activity and meteorological data from the monitored time periods. The same national analysis data sources were used to update activity and meteorology in model-extrapolated concentrations to monitored time periods (See Section 3.2, Table 2 for data source details). In addition, as with the airport-specific activity analysis, onsite observational survey data or data on the number and class of aircraft based at the airport were used to calculate piston-engine aircraft activity, as well as SE and ME activity at each airport.[69]

Figure 13 compares the rolling 3-month average model-extrapolated concentrations at the two airports with monitored data in similar locations.[70] At the airport in Panel A, two lead monitors were co-located proximate to the maximum impact area; the primary monitor is identified with a blue dot, the co-located monitor with a black dot, and the model-extrapolated concentrations (based on the lower run-up time estimates) are identified with green dots. Model-extrapolated lead concentrations at this facility are consistently lower than lead concentrations measured at the primary monitor with the difference ranging from 12% to 52% yet the Monte Carlo bounds reflecting potential variation in model-extrapolated values due to variability in run-up duration and avgas lead concentrations consistently include the primary monitored value. Model-extrapolated concentrations at the airport in Panel A identified the majority of 3-month monitored concentrations that exceeded the lead NAAQS (noted by the red line).

[69] The following percentages were used to allocate total LTOs given observational survey or based aircraft data: 70 and 86% piston-engine, 73 and 98% SE, 27% and 2% ME for each airport, respectively. See Appendix C for details on observational survey data; based aircraft data are from Airnav.com (May 2016).
[70] The time period of rolling 3-month average is used here for comparison with the lead NAAQS. Model extrapolated values presented in Figure 13 are not wind-speed adjusted.

Similarly, model-extrapolated concentrations appropriately reflect attainment of the lead NAAQS at the airport in Panel B. In this instance, both model-extrapolated (green dots) and monitored (blue dots) concentrations are below the NAAQS. In addition to providing an example of model-extrapolation performance below the NAAQS, Panel B, also provides an example of a location further downwind than the maximum impact area. At this airport, the monitor was located approximately at the 50-meter downwind model-extrapolation site, which along with activity and other parameters discussed in previous sections, explains the lower concentrations relative to the airport in Panel A.

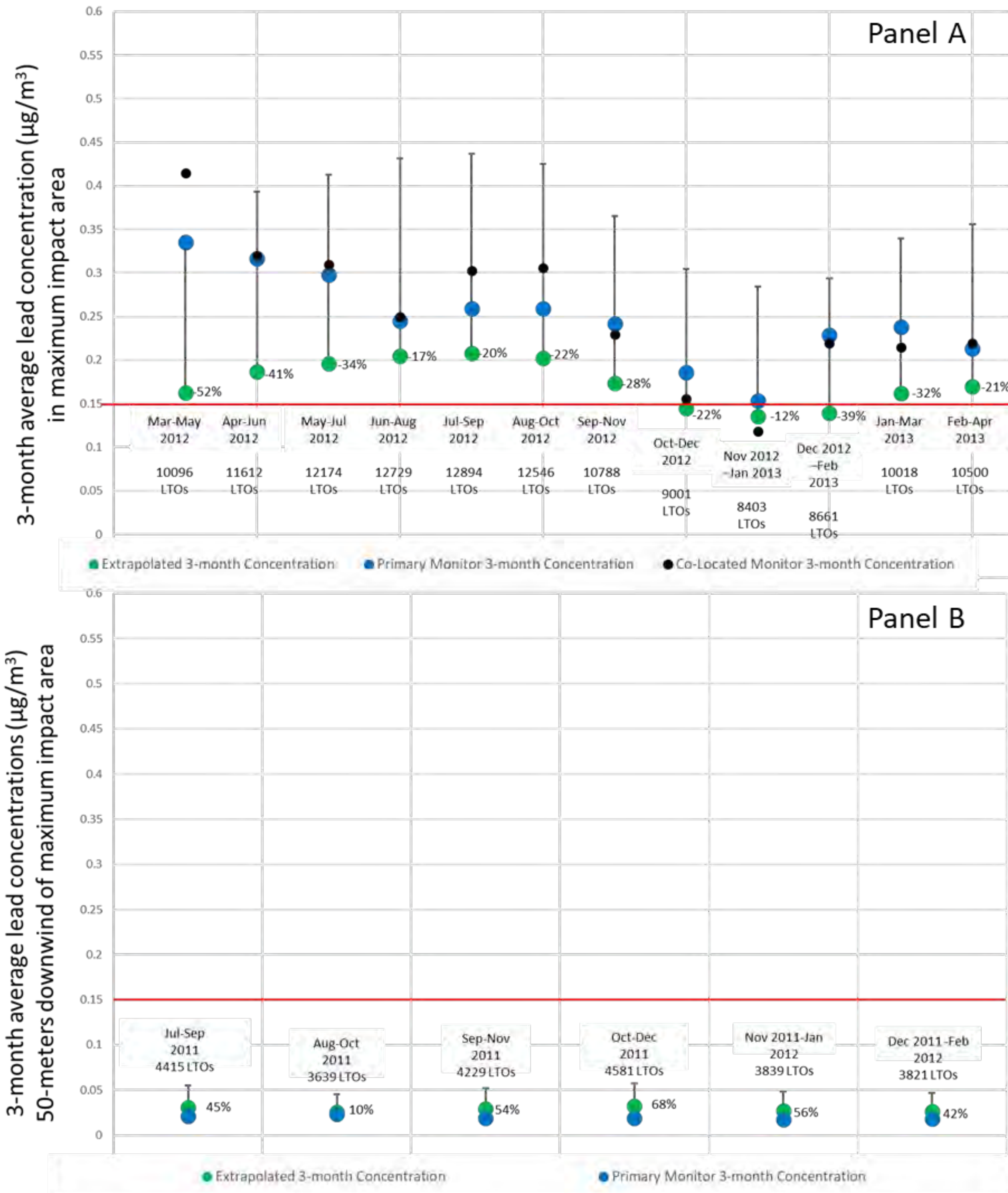


Figure 13. Comparisons of model-extrapolated (green dots) to monitored (blue and black dots) concentrations at the two airports with monitors placed proximate to model-extrapolated locations. The airport in Panel A had both a primary and co-located monitor (blue and black dots, respectively) in the maximum impact area. The airport in Panel B had a monitor approximately 50 meters downwind of the maximum impact site. The red line denotes the NAAQS for lead (i.e., rolling 3-month average of 0.15 µg/m³).

4.4 Qualitative Characterization of Uncertainty and Variability in Model-Extrapolated Lead Concentrations from National and Airport-Specific Activity Analyses

As discussed in Sections 1 and 2, emissions from piston-engine aircraft during run-up is the single largest contributor to the maximum impact area concentrations for lead from this source, and there is consistency in how and where these run-up operations are conducted across airports. The run-up emissions are released near the surface while the aircraft is stationary, occur in a flat terrain that is required for landing and take-off, and predominately impact receptor sites nearby (i.e., up to 500 meters downwind) (Carr et al. 2011, Feinberg et al. 2016) (Appendix A). While the consistent nature of piston-engine aircraft run-up emissions results in a straight-forward dispersion modeling scenario that can be used to extrapolate to other airports, key parameters impart uncertainty on the model-extrapolated results. This section qualitatively discusses additional sources of uncertainty that were not addressed in previous sections, namely uncertainty from meteorological, dispersion modeling, and operational parameters.

4.4.1 Meteorological Parameters

Several meteorological parameters affect modeled concentrations that result from dispersion modeling of pollutant emissions released at surface level. These parameters include wind speed and direction, mixing height, atmospheric stability, and ambient temperature since they directly relate to conditions of atmospheric turbulence, thermal buoyancy, as well as resulting vertical and lateral dispersion.

Low wind speeds disperse emissions less rapidly compared with high wind speeds, resulting in higher concentrations near the emissions source. Conversely, higher wind speeds result in lower concentrations near the emissions source. Specifically, as discussed in Section 3.2 and demonstrated in Appendix A, the near-field concentration of a non-reactive pollutant approximately scales with $\langle u^{-1} \rangle$, where u is wind speed and angled brackets imply a time average (Barrett and Britter 2008). Three-month average inverse wind speeds varied -23% to + 21% from the annual average wind speed. The range of inverse wind speeds at the model airport results in 3-month AQFs that vary +23% to -15% from the annual average. Approximately 51% of airports have 3-month average inverse wind speeds during the 3-month period of maximum piston-engine aircraft activity at a single runway end that fall within the range of 3-month average inverse wind speeds at the model airport.[71] Thus, we do not expect wind speed to be a significant source of uncertainty nationwide as sensitivity to wind speed will be captured by the wind speed scaling technique applied, and 3-month AQFs were only sensitive to wind speed by approximately +/-20% at the model airport. For individual airports at the extremes of high and low wind speed, we recognize there is more uncertainty in the extrapolated concentrations.[72] However, we do not expect significant GA activity during winds below 2.6 m/s or above 10.3 m/s as FAA safety recommendations state that these may be

[71] Wind speed data is from the nearest ASOS station to each airport. See Appendix A for additional information on data sources.

[72] At very low wind speeds, the inverse wind speed tends toward infinity and the wind speed scaling approach is limited by the choice of modeled minimum wind speed and the resolution of the wind monitor data.

conditions under which it is particularly challenging for a general aviation aircraft to fly (FAA 2006).

At both high and low wind speeds, significant variability in wind direction can result in additional uncertainty. When wind direction shifts significantly, airport operators may or may not initially change the runway end from which piston-engine aircraft take-off due to considerations of cross-winds and operational consistency. As noted in Section 1, airports are built such that one runway-end faces directly into the predominate wind direction, which limits the likelihood of runway-end variability. Further, Section 3.3 discusses a sensitivity analysis that evaluated the impact of shifting piston-engine aircraft operations to a specific runway-end, which addresses instances such as when wind direction variability leads to differences between the active runway-end and wind direction.

Mixing height is another meteorological condition that can influence atmospheric lead concentrations both independently and in conjunction with wind conditions. When mixing heights are very low, as is often the case overnight, then pollutants released at the surface remain trapped in the shallow surface layer, resulting in higher concentrations. Higher mixing heights occur when there is substantial surface mixing, which more rapidly disperses pollution away from the surface and result in lower surface-level concentrations. An unstable atmosphere where the mixing height is changing rapidly will also affect the concentration of lead at the maximum impact site. Previous air quality modeling conducted by EPA at individual airports characterized the influence of mixing height on modeled aircraft lead concentrations (Section 2; Appendix A) (Carr et al. 2011, Feinberg et al. 2016). At the model airport, there is a strong relationship between the 3-month average wind speeds and mixing heights (Figure 14), making it difficult to separately calculate the influence of mixing height on the AQFs. However, because run-up is the largest contributor to lead concentrations at the maximum impact site, the AQF at the maximum impact site is not expected to be sensitive to local mixing height. Concentrations at sites downwind may be more sensitive to mixing height and atmospheric stability, particularly during long periods of atmospheric inversion or at airports that have mixing height characteristics significantly different from the model airport.

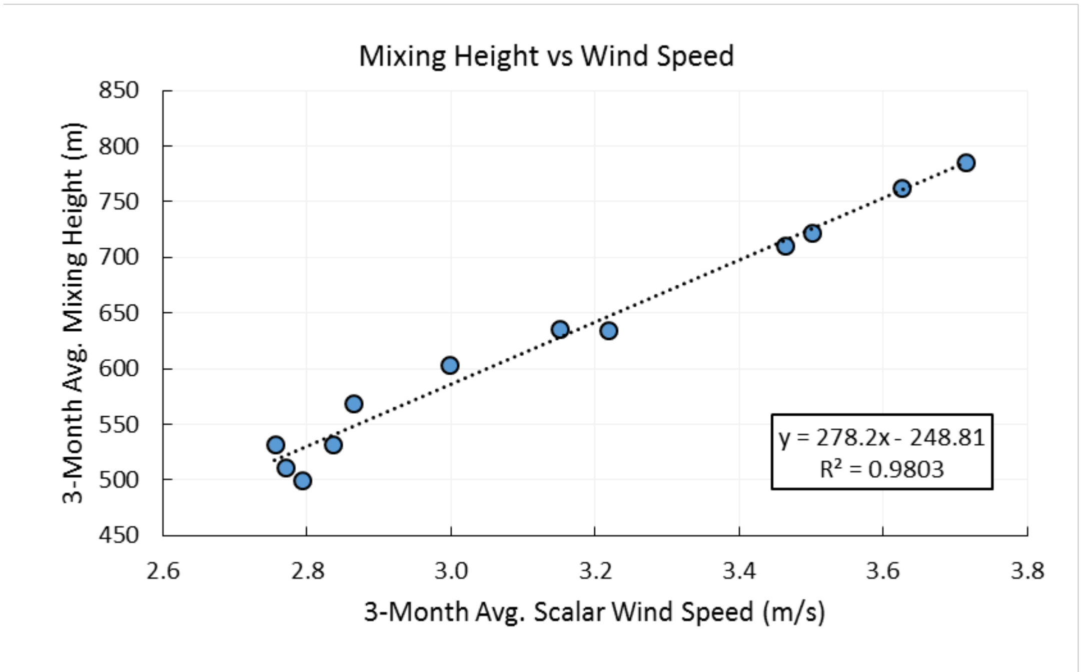


Figure 14. 3-month average mixing height at the model airport as a function of 3-month average scalar wind speed at the model airport over the same period.

Microclimate conditions and other meteorological parameters may contribute to some variability in the relationship between aircraft operations and resulting atmospheric lead concentrations. For example, near-source maximum primary pollutant concentrations have shown some dependence on ambient air temperature, but to a lesser extent than wind speed (Liang et al. 2013). A preliminary analysis of 3-month AQFs at the model airport showed that temperature was a significant variable (p-value =0.001046) when controlling for average inverse wind speed; however, because average 3-month temperature varied by less than +/-2% at the model airport, maximum impact and downwind concentrations were not sensitive to ambient temperature. Thus, while results nationwide are not expected to be particularly sensitive to microclimate conditions and other meteorological variables, there is more uncertainty in model-extrapolated concentrations at airports that have maximum activity periods during meteorological conditions not observed at the model airport.

4.4.2 AERMOD and AERSURFACE Parameters

Modeling parameters in AERMOD may be a source of both aleatoric and epistemic uncertainty. [73] Near-field surface and geographic characteristics may have an impact on lead concentrations at and downwind of the maximum impact site. The calculation of AQFs included a fixed parameterization of surface roughness, Bowen Ratio, and albedo as described in Appendix A,

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[73] Uncertainty can be classified into aleatoric uncertainty and epistemic uncertainty. Aleatoric uncertainty is often characterized as natural randomness that is often difficult to measure. Epistemic uncertainty is typically characterized as uncertainty due to the lack of data (e.g., data that could be collected but the methods may be prohibitive).

but downwind surface characteristics may differ at airports nationwide. Other research has suggested that, at certain receptors, modelled AERMOD concentrations are sensitive to changes in surface roughness length but indifferent to albedo and Bowen Ratio variation (Grosch and Lee 2000, Karvounis et al. 2007). Further, the modeling approach does not necessarily account for complex airflow around or near buildings and other obstructions. While these factors may cause uncertainty at downwind concentrations, their impact on variability near the maximum impact site is mitigated by requirements for on-airport characteristics and land-use immediately downwind of runways due to landing and take-off safety requirements, which results in some consistency nationwide. Where obstructions such as noise barriers or fences may impact atmospheric lead concentrations near the maximum impact site, extrapolated concentrations and their associated uncertainty should be considered on a case-by-case basis. Finally, the aircraft were modeled as volume sources with fixed horizontal and vertical plume extents, which may introduce uncertainty at airports with aircraft and engines that differ significantly from those at the model airport. Details on the modeling approach for aircraft sources, information on prior modeling work, and a comparison between piston-engine aircraft included in the model airport modeling with those active at airports nationwide is provided in Appendix A.

4.4.3 Operational Parameters

As discussed throughout the report, the availability, resolution, type, and detail of operational data available at airports nationwide can contribute to uncertainty in the estimated lead concentrations. The impact of airport-specific fleet heterogeneity (i.e. piston/turboprop split and single-engine/multi-engine split) was explored through the use of airport-specific data for a subset of airports in Section 4.2. However, other local fleet characteristics (e.g. distribution of aircraft engine types operating at the airport) are not accounted for in the analysis and may also contribute to uncertainty at specific airports that have distinct local characteristics. The nature of piston engines means that there is also a great deal of variability in their emissions, even for the same pilot operating the same airplane (Yacovitch et al. 2016); however, the sensitivity of atmospheric lead concentrations to this variability should be minimized by averaging concentrations over a 3-month period. Similarly, the diurnal profile of aircraft activity may influence local lead concentrations over short timescales, but is not expected to be a sensitive parameter in determining 3-month average concentrations as discussed in Appendix B. Regional, local, and seasonal differences in daily operational patterns may contribute additional uncertainty to that discussed in Appendix B. However, given the insensitivity of average concentrations to different diurnal patterns in sensitivity analysis modeling, these are not expected to contribute significantly to uncertainty in extrapolated concentration estimates for airports nationwide. In modeling individual airports, national fleet and operational data should be supplemented with local data where available and feasible.

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Appendices

Appendix A: Supplemental Information on Detailed Air Quality Modeling at a Model Airport

As described in Section 2, factors that relate aircraft activity to resulting air lead concentrations, referred to as Air Quality Factors (AQFs), are used to estimate atmospheric lead concentrations at airports nationwide by extrapolating the relationship between the number of piston-engine aircraft landing-and-take-off operations (LTOs) and the resulting atmospheric lead concentrations. The AQFs were developed through detailed air quality modeling at a model airport. This appendix provides details on the air quality modeling used to develop the AQFs and the model airport at which they were developed. Specifically, details on three topic areas are included in the sections below: A.1) the air quality modeling setup, input data, and parameters; A.2) characterization of the air quality model performance through model-to-monitor comparisons at the model airport; A.3 and A.4) characteristics of the model airport fleet composition and the fuel consumption rates that are incorporated into the AQFs; and A.5) details of the wind speed adjustment methodology to scale AQFs based on average inverse wind speed during.

A.1 Details Regarding Air Quality Modeling at the Model Airport

This section provides information used to conduct detailed air quality modeling at the model airport. Specifically, the subsections below present: 1) input data and methods to develop aircraft emissions inventories, 2) non-aircraft emissions inventory data, 3) meteorological inputs, 4) model receptors, and 5) the characterization of emission sources and receptors.

A.1.1 Aircraft Activity, Source Locations, and Emissions

Two aircraft emissions inventories were developed for this analysis: a seven-day inventory to facilitate model-to-monitor comparison, and an annual operations inventory used to generate the 3-month average AQFs. Both inventories were developed from a combination of published Federal Aviation Administration (FAA) Air Traffic activity data and on-site surveys. This section presents the underlying data and methods used to develop both inventories. The annual emissions inventory and its use in developing the AQFs at the model airport are further described in Section 2.3 of the report.

Aircraft Activity Surveys

Surveyors collected aircraft operations data at RHV for the following ten days in 2011 from 10 a.m. until 7 p.m. local time.[1]

[1] Bolded dates correspond to those when aircraft surveys were conducted *and* when lead air concentration monitoring was conducted. Both aircraft activity and lead monitoring data were collected on the predominantly active runway (Runway 31R). Monitor data was collected for 8/20, southerly winds resulted in operations occurring predominantly on Runway 13L; therefore, model-to-monitor comparisons were not used for this day.

- 8/14 Sunday
- 8/17 Wednesday
- **8/20 Saturday**
- **8/23 Tuesday**
- **8/26 Friday**
- **8/28 Sunday**
- 9/1 Thursday
- 9/3 Saturday
- 9/5 Monday
- 9/7 Wednesday

The collected data included runway location, aircraft tail fin number (N-Number), LTO mode (taxi-out, run-up, take-off, climb, approach, landing, or taxi-in), duration of LTO mode (time-in-mode), and other details about the aircraft activity (e.g., touch-and-go, altitude at approach, altitude at departure). Whenever possible the surveyors visually identified the aircraft type. Where aircraft type was not visually identified, the recorded tail fin numbers were matched to the FAA tail number registry to obtain the type and number of engines. To match local typical airport flight patterns, surveyors attempted to record the timing of approaches beginning at 1,100 ft (335 m) by listening to the control tower broadcast; the surveyors stopped timing climbs at the same height. For those altitudes recorded lower or higher, adjustments were made to normalize the time-in-mode for climb and approach to 1,100 ft. 5.6% of survey entries were flagged as invalid, largely due to missing or incorrectly recorded time data.

Hourly and Daily Aircraft Activity Estimates

Hourly activity profiles for each aircraft class [single engine (SE), multi-engine (ME) and rotorcraft (R)] and each operation-cycle type [full landing and take-off (LTO) and touch-and-go (T&G)] were developed from the 10 days of survey data described above[2]. For morning and evening hours when survey data was not available, the percentage of total daily flights occurring in each hour was taken from a prior survey of piston-aircraft operations at another airport (Carr et al. 2011). Total daily operations were estimated by adjusting the surveyed operational counts to match FAA Air Traffic Activity Data System (ATADS) operation counts for itinerant-general aviation and local-civil activity to account for operations that may have been missed or mis-categorized by surveyors. The adjustment factor equation is given below in Equation A-1. The adjustment factors for the ten days ranged from 1.02 to 1.23.

[2] As described in Section 4.3 a Monte Carlo analysis was conducted to evaluate variation run-up duration, since as discussed in Section 2, this mode of operation has the most significant impact on downwind lead concentrations. The Monte Carlo analysis draws from additional airport studies and incorporates a range of run-up durations that can account for variation due to a variety of factors (e.g., seasonal changes, regional differences, individual airport characteristics). See Section 4.3 for additional details on the Monte Carlo analysis.

$$R_{Adj} = \frac{\frac{A_{Daily,\ ATADS}}{2} - \sum A_{Off\ Hours}}{\sum A_{On\ Hours,\ Survey}} \qquad \text{(Equation A-1)}$$

Where:

R_{Adj} = the adjustment factor, used ensure estimated aircraft activity counts based on surveyed data matched daily ATADS counts;

$A_{On\ Hours,\ Survey}$ = the hourly aircraft activity counts when surveys were conducted, according to the survey data. This is the sum of all surveyed counts of the aircraft and operation types selected for modeling;

$A_{Off\ Hours}$ = the hourly LTO count when surveys were not conducted; and

$A_{Daily,\ ATADS}$ = the daily operations from ATADS. The ATADS data reports "operations" which sums arrivals and departures. Because activity is modeled as landing and take-off cycles (LTOs), operations are divided by 2.

For fixed-wing, multi-engine aircraft the relative scarcity of data led to some hours containing very small operational counts. Thus, for these aircraft types, instead of scaling operational counts for each hour, operational counts were scaled for the entire day and the incremental increase in operations was divided evenly across all hours with non-zero survey counts. This incremental adjustment led to fractional operations being modeled for multi-engine aircraft for some hours on some days. For all aircraft types, the adjusted hourly activity counts for each day were used in three of the seven days in the emissions inventory developed for model-to-monitor comparisons. These three days corresponded to those with overlapping monitor and survey data. For the remaining four days, the inventory used the average of the adjusted activity profiles across all ten survey days.

Aircraft Emission Rates

Piston engines operating on leaded fuel can emit lead in both the gaseous and particulate form. Aviation fuels containing tetraethyl lead also contain ethylene dibromide as an additive to prevent lead from depositing within the engine. Lead reacts with the ethylene dibromide to form brominated lead compounds. These brominated lead compounds are exhausted as vapors but quickly cool and condense to solid particles. In contrast, organic lead emissions remain as vapors after cooling to ambient temperatures (USEPA 2013b). A fraction of lead is retained in the engine, engine oil, and/or exhaust system, which is estimated in this work at 5% (USEPA 2013a).

Equation A-2 was used to calculate lead emission rates as a function of the mode specific fuel consumption rate.

$$\text{Emissions}(\text{g}\cdot\text{s}^{-1}) = \frac{\text{Time(s)}\times\left(\frac{\text{fuel consumed(g)}}{\text{s}}\right)\times\left(\frac{\text{Engines}}{\text{Hour}}\right)\times\left(\frac{\text{Pb(g)}}{\text{gal}}\right)\times(1\text{-RetRate})}{\left(\frac{\text{fuel weight(g)}}{\text{gal}}\right)\times\left(\frac{\text{Seconds}}{\text{Hour}}\right)} \qquad \text{(Equation A-2)}$$

Where:

Time(s) = the time (seconds) in mode;

$\frac{\text{fuel consumed(g)}}{\text{s}}$ = the amount (grams) of fuel consumed per second for one engine in a given LTO mode;

$\frac{\text{Engines}}{\text{Hour}}$ = the number of engines operating each hour;[3]

$\frac{\text{Pb(g)}}{\text{gal}}$ = the concentration (g/gal) of Pb in avgas (2.16 g/gal, the average Pb concentration measured in avgas from RVH);

RetRate = the fraction of Pb retained in the engine after fuel consumption (0.05);[4]

$\frac{\text{fuel weight (g)}}{\text{gal}}$ = the weight (g) of avgas fuel per gallon (2,730.6 g/gal); and

$\frac{\text{Seconds}}{\text{Hour}}$ = the number of seconds per hour (3,600 s);

Aircraft emissions profiles for each hour were developed by calculating hourly fuel consumption for each aircraft type by operational mode (taxi, run-up, take-off, climb, approach, landing). Total fuel consumption is a function of the time spent in each operational mode and the fuel consumption rate of the aircraft's engine(s) during that mode. Aircraft class-specific (SE, ME, R) median times-in-mode for each operational mode were developed for each hour for each of the 10 survey days. Use of median times-in-mode avoided biasing fuel consumption high for activities such as run-up which had occasional aircraft with unusually long activity durations or biasing fuel consumption low for activities such as approach where surveyors may have recorded short durations as a result of not knowing of an aircraft approach until it was on final approach and well below the 1,100 feet nominal height. For hours when surveys were not conducted, the inventory assumes the median of all recorded data for that activity mode. For

[3] Two engines for multi-engine fixed-wing aircraft, one for single-engine fixed-wing aircraft

[4] The information used to develop this estimate is from the following references: (a) Todd L. Petersen, Petersen Aviation, Inc, *Aviation Oil Lead Content Analysis*, Report # EPA 1-2008, January 2, 2008, available at William J. Hughes Technical Center Technical Reference and Research Library at http://actlibrary.tc.faa.gov/ and (b) E-mail from Theo Rindlisbacher of Switzerland Federal Office of Civil Aviation to Bryan Manning of U.S. EPA, regarding lead retained in engine, September 28, 2007.

the 3 days of overlapping monitor and survey data, the corresponding day-specific hourly median times-in-mode were used in the emissions inventory. For the remaining 4 days, each day was assigned the same median hourly TIM values.

Published fuel consumption data was used to develop engine- and mode-specific fuel consumption rates. Fuel consumption data by operational mode was available for 18 engines from FAA's Emission and Dispersion Modeling System and the Swiss Federal Office of Civil Aviation report on piston-engine emissions (FAA 2007, SFOCA 2007). These data spanned the range of engine technology groups (fuel injected, turbocharged, carbureted, radial) observed at the airport. Where observed aircraft had specific engine types (e.g., 4-stroke radial, 2-stroke fuel injected) not in the fuel consumption database, fuel consumption for that aircraft was modeled using the engine type with the closest rated horsepower in the same engine technology group. Further details on the mode-specific fuel consumption rates are given in Section A.4.

Aircraft Emission Inventories

The above calculation of emission rates was used to develop two separate emissions inventories. As noted above, both a seven-day and annual emissions inventory were developed for two distinct purposes, but using similar methods. The seven-day emissions inventory was used to facilitate model-to-monitor comparison for the days in which survey data and on-site monitoring were conducted concurrently, and as such used the highly resolved hourly operational data from on-site survey data described above. The annual inventory was used to calculate 3-month average concentrations (and derived AQFs), and thus required emissions modeling for 14 months to understand 12 consecutive, 3-month rolling-average concentrations. Absent detailed on-site monitoring data for aircraft and engine types and hourly operations for each day of the 14 months, the annual emissions inventory used the average operational profile, median time-in modes and fuel consumption rates, and ATADs operations data as described in Section 2.3 of the main report. Aircraft emissions for months 13 and 14 were taken from months 1 and 2 respectively so that rolling-average concentrations represented concentrations from a consistent year of emissions. The total lead emissions from aircraft (in tons) are given by month and operational mode in Table A-1. (Lead emissions included in the modeling from other sources are described in Tables A-2 through A-6.)

Table A-1. Monthly and annual lead emissions from aircraft (tons)

		Aircraft Mode							Total of all Aircraft Modes
Activity	**Month**	**Taxi-out**	**Run-Up**	**Take-off**	**Climb**	**Approach**	**Landing**	**Taxi-in**	
ME Full LTO	01	1.16E-04	5.85E-05	3.28E-05	3.82E-05	1.61E-05	7.05E-06	1.99E-05	2.88E-04
	02	9.40E-05	4.52E-05	2.73E-05	2.94E-05	1.34E-05	6.15E-06	1.59E-05	2.32E-04
	03	1.23E-04	6.00E-05	3.53E-05	3.90E-05	1.74E-05	7.85E-06	2.08E-05	3.03E-04

Activity	Month	Aircraft Mode							Total of all Aircraft Modes
		Taxi-out	Run-Up	Take-off	Climb	Approach	Landing	Taxi-in	
	04	9.85E-05	4.61E-05	2.87E-05	2.99E-05	1.41E-05	6.55E-06	1.64E-05	2.40E-04
	05	1.15E-04	5.55E-05	3.31E-05	3.62E-05	1.63E-05	7.40E-06	1.94E-05	2.83E-04
	06	1.24E-04	5.85E-05	3.57E-05	3.80E-05	1.76E-05	8.10E-06	2.07E-05	3.02E-04
	07	1.29E-04	6.20E-05	3.71E-05	4.02E-05	1.83E-05	8.30E-06	2.17E-05	3.16E-04
	08	1.31E-04	6.25E-05	3.77E-05	4.05E-05	1.86E-05	8.50E-06	2.19E-05	3.20E-04
	09	1.11E-04	5.35E-05	3.18E-05	3.48E-05	1.56E-05	7.10E-06	1.87E-05	2.72E-04
	10	1.06E-04	5.15E-05	3.04E-05	3.36E-05	1.50E-05	6.75E-06	1.79E-05	2.61E-04
	11	9.15E-05	4.16E-05	2.69E-05	2.68E-05	1.32E-05	6.30E-06	1.51E-05	2.21E-04
	12	7.20E-05	3.18E-05	2.13E-05	2.04E-05	1.05E-05	5.05E-06	1.17E-05	1.73E-04
	Annual Total	**1.31E-03**	**6.27E-04**	**3.78E-04**	**4.07E-04**	**1.86E-04**	**8.51E-05**	**2.20E-04**	**3.21E-03**
ME T&G	01	--	--	--	2.08E-05	1.31E-05	--	--	3.38E-05
	02	--	--	--	1.81E-05	1.22E-05	--	--	3.03E-05
	03	--	--	--	2.31E-05	1.53E-05	--	--	3.84E-05
	04	--	--	--	1.94E-05	1.35E-05	--	--	3.29E-05
	05	--	--	--	2.19E-05	1.46E-05	--	--	3.65E-05
	06	--	--	--	2.39E-05	1.63E-05	--	--	4.02E-05
	07	--	--	--	2.45E-05	1.65E-05	--	--	4.10E-05
	08	--	--	--	2.51E-05	1.69E-05	--	--	4.20E-05
	09	--	--	--	2.09E-05	1.39E-05	--	--	3.48E-05
	10	--	--	--	1.99E-05	1.32E-05	--	--	3.31E-05
	11	--	--	--	1.86E-05	1.33E-05	--	--	3.19E-05
	12	--	--	--	1.50E-05	1.10E-05	--	--	2.60E-05
	Annual Total	**0.00E+00**	--	--	**2.51E-04**	**1.70E-04**	--	--	**4.21E-04**
SE Full LTO	01	8.20E-04	3.62E-04	3.09E-04	3.81E-04	3.12E-04	6.65E-05	2.23E-04	2.48E-03
	02	7.15E-04	3.16E-04	2.70E-04	3.20E-04	2.66E-04	5.75E-05	1.96E-04	2.14E-03
	03	9.15E-04	4.03E-04	3.44E-04	4.13E-04	3.42E-04	7.35E-05	2.49E-04	2.74E-03
	04	7.70E-04	3.38E-04	2.89E-04	3.38E-04	2.83E-04	6.20E-05	2.11E-04	2.29E-03
	05	8.65E-04	3.81E-04	3.25E-04	3.89E-04	3.22E-04	6.95E-05	2.36E-04	2.59E-03
	06	9.45E-04	4.17E-04	3.56E-04	4.20E-04	3.51E-04	7.60E-05	2.59E-04	2.83E-03

Activity	Month	Aircraft Mode							Total of all Aircraft Modes
		Taxi-out	Run-Up	Take-off	Climb	Approach	Landing	Taxi-in	
	07	9.70E-04	4.27E-04	3.65E-04	4.35E-04	3.61E-04	7.80E-05	2.65E-04	2.90E-03
	08	9.90E-04	4.37E-04	3.73E-04	4.42E-04	3.68E-04	8.00E-05	2.71E-04	2.96E-03
	09	8.25E-04	3.64E-04	3.11E-04	3.72E-04	3.09E-04	6.65E-05	2.26E-04	2.48E-03
	10	7.90E-04	3.47E-04	2.96E-04	3.56E-04	2.95E-04	6.35E-05	2.15E-04	2.36E-03
	11	7.35E-04	3.24E-04	2.77E-04	3.18E-04	2.69E-04	5.90E-05	2.02E-04	2.19E-03
	12	5.95E-04	2.61E-04	2.24E-04	2.53E-04	2.15E-04	4.77E-05	1.64E-04	1.76E-03
	Annual Total	**9.94E-03**	**4.37E-03**	**3.74E-03**	**4.43E-03**	**3.69E-03**	**8.00E-04**	**2.72E-03**	**2.97E-02**
SE T&G	01	--	--	--	2.86E-04	2.79E-04	--	--	5.65E-04
	02	--	--	--	2.44E-04	2.42E-04	--	--	4.86E-04
	03	--	--	--	3.13E-04	3.09E-04	--	--	6.20E-04
	04	--	--	--	2.60E-04	2.59E-04	--	--	5.20E-04
	05	--	--	--	2.96E-04	2.92E-04	--	--	5.90E-04
	06	--	--	--	3.21E-04	3.20E-04	--	--	6.40E-04
	07	--	--	--	3.31E-04	3.28E-04	--	--	6.60E-04
	08	--	--	--	3.38E-04	3.35E-04	--	--	6.70E-04
	09	--	--	--	2.83E-04	2.80E-04	--	--	5.60E-04
	10	--	--	--	2.70E-04	2.67E-04	--	--	5.35E-04
	11	--	--	--	2.46E-04	2.48E-04	--	--	4.94E-04
	12	--	--	--	1.97E-04	2.00E-04	--	--	3.97E-04
	Annual Total	**--**	**--**	**--**	**3.39E-03**	**3.36E-03**	**--**	**--**	**6.75E-03**
Annual Total		**1.20E-02**	**5.00E-03**	**4.25E-03**	**8.48E-03**	**7.40E-03**	**8.99E-04**	**3.16E-03**	**4.12E-02**

Aircraft Source Locations

Both the seven day and annual emissions inventories are spatially allocated at the model airport to characterize resulting atmospheric concentrations. A three-dimensional representation of the modeled aircraft source locations is provided in **Error! Reference source not found.** A-1 for northwest take-offs and in Figure A-2 for southeast take-offs. All ground-level release heights were set to 0.5 meter to represent the approximate aircraft exhaust height. For taxi activity, emission sources were placed approximately 50 meters apart along two taxiways – one directly adjacent to the terminal and hangars, and one along a separate taxiway to the west of the first taxiway. For run-up activity, two run-up locations were modeled near the terminus of both taxiways. The two run-up locations were approximately 8 meters apart at both ends of the taxi-way. For modes at altitude (i.e., climb and approach), emissions sources had 50 meters horizontal spacing and ascent/descent angles of 4.7 and 3.8 degrees respectively, angles similar to those used in the SMO study (Carr et al. 2011).[5] Airport noise ordinances dictate that aircraft using runway 31R (northwest takeoff) make a 30-degree right turn after departing the runway and after climbing to an altitude of at least 500 feet above ground level.

[5] This also includes a consideration to account for the wake turbulence created by the forces that lift the aircraft. High pressure air from the lower surface of the wings flows around the wing tips to the lower pressure region above the wings. A pair of counter-rotating vortices is shed from the wings where the right and left wing vortices rotate. It is within this region of rotating air behind the aircraft where wake turbulence occurs. To account for this effect, the effective emission height was adjusted for the angle of climb (takeoff) and glide slope angle for landing. This adjustment lowers the effective emission height to approximate the maximum downward extent of the aircraft's trailing wake. This results in an angle of climb-out for take-off of approximately 4.7 degrees, while for landing this was 3.8 degrees.

Satellite Image Source: ESRI Prime Imagery 3D

The aircraft release heights are at each colored sphere. Symbol shadings correspond to release heights, where green values are close to the surface and dark red values are approximately 145 m above the surface. Satellite photography and terrain features are shown. Vertical terrain height is exaggerated. The point of view is elevated, approximately 2.3 km away and facing northeast.

Figure A-1. Modeled aircraft emission source locations for northwest take-offs, in three dimensions

Satellite Image Source: ESRI Prime Imagery 3D

The aircraft release heights are at each colored sphere. Symbol shadings correspond to release heights, where green values are close to the surface and dark red values are approximately 145 m above the surface. Satellite photography and terrain features are shown. Vertical terrain height is exaggerated. The point of view is elevated, approximately 2.3 km away and facing northeast.

Figure A-2. Modeled aircraft emission source locations for southeast take-offs, in three dimensions

A.1.2 Emissions from Sources Other than Aircraft

Data on emissions from sources other than aircraft operating at the model airport was collected in order to include these sources in the modeled concentrations that would be compared to monitored concentrations, the latter of which of course included atmospheric lead from any source. For purposes of modeling, these non-aircraft emissions include rotorcraft at the model airport, point sources, nearby road sources, mobile and area sources, and background lead within 20 km of the airport.

Rotorcraft

Piston-engine Rotorcraft activity estimates at the model airport were generated using the same methodology described above for fixed-wing single- and multi-engine aircraft. Daily surveys were combined with activity counts from ATADS data to develop hourly rotorcraft activity profiles. Rotorcraft parking was assumed to be near the model airport terminal, and take-offs occurred at a 4.7 degree trajectory from Runway 31R and Runway 13L, or vertically from a helicopter practice area (also called the haypatch). As with fixed-wing aircraft at the model airport, rotorcraft at the model airport were modeled as volume sources as described in section A.1.5 with 2.3 vertical meters between source points in landing and take-off as shown in Figures A-1 and A-2. Monthly and annual emissions from rotorcraft are given in Table A-2. Nearby heliports (i.e. rotorcraft landing and takeoffs not occurring at the model facility) were modeled as area sources.

Table A-2. Monthly rotorcraft emissions at the model airport (tons)

Location	Month	Taxi-out	Take-off	Landing	Taxi-in	Total
31R/13L	01	3.38E-05	4.88E-06	1.29E-06	9.10E-06	4.90E-05
	02	2.78E-05	4.75E-06	1.03E-06	8.15E-06	4.17E-05
	03	3.61E-05	5.85E-06	1.35E-06	1.03E-05	5.35E-05
	04	2.92E-05	5.30E-06	1.07E-06	8.80E-06	4.43E-05
	05	3.39E-05	5.65E-06	1.26E-06	9.80E-06	5.05E-05
	06	3.64E-05	6.35E-06	1.35E-06	1.08E-05	5.50E-05
	07	3.79E-05	6.40E-06	1.41E-06	1.10E-05	5.65E-05
	08	3.84E-05	6.60E-06	1.43E-06	1.13E-05	5.75E-05
	09	3.25E-05	5.35E-06	1.21E-06	9.35E-06	4.84E-05
	10	3.11E-05	5.05E-06	1.16E-06	8.90E-06	4.62E-05
	11	2.72E-05	5.30E-06	9.85E-07	8.55E-06	4.20E-05
	12	2.14E-05	4.43E-06	7.65E-07	6.95E-06	3.36E-05
	Annual Total	**3.85E-04**	**6.59E-05**	**1.43E-05**	**1.13E-04**	**5.78E-04**
	01	3.38E-05	4.88E-06	--	9.10E-06	4.77E-05

Location	Month	Taxi-out	Take-off	Landing	Taxi-in	Total
Haypatch	02	2.78E-05	4.75E-06	--	8.15E-06	4.07E-05
	03	3.61E-05	5.85E-06	--	1.03E-05	5.20E-05
	04	2.92E-05	5.30E-06	--	8.80E-06	4.33E-05
	05	3.39E-05	5.65E-06	--	9.80E-06	4.93E-05
	06	3.64E-05	6.35E-06	--	1.08E-05	5.35E-05
	07	3.79E-05	6.40E-06	--	1.10E-05	5.50E-05
	08	3.84E-05	6.60E-06	--	1.13E-05	5.65E-05
	09	3.25E-05	5.35E-06	--	9.35E-06	4.72E-05
	10	3.11E-05	5.05E-06	--	8.90E-06	4.51E-05
	11	2.72E-05	5.30E-06	--	8.55E-06	4.10E-05
	12	2.14E-05	4.43E-06	--	6.95E-06	3.28E-05
	Annual Total	**3.85E-04**	**6.59E-05**	**--**	**1.13E-04**	**5.64E-04**

Point Sources

Sixteen point sources of lead emissions within approximately 20 km of the model airport were modeled based on emissions data from the 2008 National Emissions Inventory (version 1.5) (USEPA 2011). Excluded from the point source inventory were approximately 122 facilities that each emit less than 1E-05 US Tons per year (TPY) of lead (totaling 1.8E-04 TPY or 0.36 lbs/yr), which is more than a factor of 100 times smaller than the model airport aircraft emissions. The hourly emissions profiles for point sources were approximated using the temporal codes that the Bay Area Air Quality Management District (BAAQMD) used for Community Air Risk Evaluation (CARE) modeling (BAAQMD 2011). Point source facility descriptions and emissions magnitudes are given in Table A-3.

Table A-3. Industries corresponding to the 16 modeled facilities within 20 km of the Model Airport

Source Description	Number of Facilities	Modeled Pb Emissions (TPY)[a]	Emissions Percentage of Total Point
San Jose Airport – Piston-engine emissions	1	1.82×10^{-1}	98.86%
Heliports	4	1.41×10^{-3}	0.77%
Nonferrous Metal (except Aluminum) Production and Processing	1	2.87×10^{-4}	0.16%
Aerospace Product and Parts Manufacturing	1	1.29×10^{-4}	0.07%
Computer Storage Device Manufacturing, Data Processing, Hosting, and Related Services	2	7.25×10^{-5}	0.04%
Crematorium	2	5.40×10^{-5}	0.03%

Source Description	Number of Facilities	Modeled Pb Emissions (TPY)[a]	Emissions Percentage of Total Point
Dry cleaning and Laundry Services	1	4.75×10^{-5}	0.03%
Commercial and Service Industry Machinery Manufacturing	1	2.70×10^{-5}	0.01%
Water, Sewage and Other Systems	1	2.70×10^{-5}	0.01%
General Medical and Surgical Hospitals	1	2.50×10^{-5}	0.01%
Recyclable Material Merchant Wholesalers	1	2.10×10^{-5}	0.01%
TOTAL	**16**	**1.84×10^{-1}**	**100%**

[a] San Jose Airport emissions are representative of 2015. All other emissions in this Table are representative of 2008.

Nearby Road Sources

Lead emissions were modeled from three roadways in close proximity to the airport. Time-varying emission rates were calculated from a combination of diurnal traffic count data, the area of each roadway, and a mobile lead emissions per mile traveled estimate. The hot stabilized summer emission factor of 0.002 mg of Pb/mile was used for gasoline vehicles, and an emission factor of 0.00724 mg/mile was used for diesel fueled trucks and buses (USEPA 2006). The total annual average lead emissions from all three adjacent roadways was $4.3\text{x}10^{-5}$ TPY. The location of the roadway emissions sources is shown in Figure A-3, and roadway characteristics are given in Table A-4.

Figure A-3. Explicitly modeled road sources adjacent to the model airport

Table A-4. Collected input data for explicitly modeled road sources adjacent to the model airport

Street	Length of Road (m)	Area of Road (m^2)	Average Daily Traffic (ADT)	Year of ADT Data
East Capitol Expressway	1223.10	50661.24	40,700	2008
Tully Road	643.74	22457.86	33,676	2010
Ocala Avenue	740.30	12355.21	10,867	2009

Gridded Area, On-Road Mobile, and Non-Road Mobile Sources

Lead emissions from area,[6] non-road mobile,[7] and on-road mobile sources[8] within approximately 20 km of the model airport were modeled in 1x1-km grid cells using an annual

[6] Area (non-mobile) sources included agricultural and livestock waste, cooking, wind erosion, mining, and open burning and other fires.

[7] Non-road mobile sources included military aircraft, commercial aircraft, airport support vehicles, construction and other road dust, agricultural and commercial off-road vehicles, railroad equipment, and marine and pleasure craft.

[8] On-road mobile sources included lead emissions based on California's Emission Inventory Reporting System PM speciation profiles database which includes tire and brake wear from light- and heavy-duty vehicles and diesel fueled vehicle exhaust emissions. The speciation profile has zero lead emissions from gasoline exhaust. Emissions

year 2015 projection inventory developed previously by a local agency (BAAQMD 2011). The total modeled emissions are shown in Table A-5 (for on-road mobile) and Table A-6 (for non-road mobile plus area).

Table A-5. Modeled on-road mobile gridded Pb emissions within 20 km of the model airport

Source Description	Pb Emissions (TPY)	Emissions Percentage of Total On-Road Mobile
Highway Vehicle - Tire Wear	2.27×10^{-5}	59%
Highway Vehicle - Brake Wear	1.06×10^{-5}	27%
Highway Vehicle - Diesel Exhaust	5.30×10^{-6}	14%
TOTAL	$\mathbf{3.86\times10^{-5}}$	**100%**

Table A-6. Modeled non-road mobile and area gridded lead emissions within 20 km of the model airport

Source Description	Pb Emissions (TPY)	Emissions Percentage of Total Non-Road Mobile and Area
Construction: Industrial, Commercial, Institutional, Residential, Road Construction	3.37×10^{-3}	50.96%
Paved Roads	1.84×10^{-3}	27.85%
Food and Kindred Products: Commercial Cooking and Miscellaneous	7.10×10^{-4}	10.73%
Agriculture Production - Livestock	2.10×10^{-4}	3.17%
Military and Commercial Aircraft	2.08×10^{-4}	3.14%
Geogenic Wind Erosion	1.34×10^{-4}	2.03%
Residential Oil and Wood Burning	5.60×10^{-5}	0.85%
Mineral Processes: Concrete, Gypsum, Plaster	3.39×10^{-5}	0.51%
Unpaved Roads	2.59×10^{-5}	0.39%
Forest Wildfires, Prescribed Burns, Motor Vehicle Fires	1.24×10^{-5}	0.19%
Off-highway Vehicle Diesel (incl. Airport Ground Support Equipment)	5.38×10^{-6}	0.08%
Agriculture Production - Crops	3.15×10^{-6}	0.05%
Railroad Equipment	1.82×10^{-6}	0.03%

from the nearby roadways were explicitly modeled. Because of the differences in inventory years, fuel emission rates, and accounting for break and tire wear in these two inventories, the combined gridded emissions may result in some small double-counting or undercounting of lead emissions from brake and tire wear and vehicle exhaust in the modeling domain.

Source Description	Pb Emissions (TPY)	Emissions Percentage of Total Non-Road Mobile and Area
Open Burning	7.90×10^{-7}	0.01%
Agriculture Production - Crops - as nonpoint	4.30×10^{-7}	0.01%
Pleasure Water Craft	5.61×10^{-9}	0.0001%
TOTAL	**6.61×10^{-3}**	**100%**

Background Emissions

The background ambient lead concentration was set to 0.5 ng/m^3, the pristine background ambient lead concentration used by the EPA Office of Air Quality Planning and Standards Regulatory Impact Analysis for the lead National Ambient Air Quality Standard (NAAQS) (USEPA 2008b).

A.1.3 Meteorology

Meteorological Data

Surface and upper-air meteorological data were processed using AERMOD's meteorological preprocessor, AERMET, to produce hourly data on mixing heights, stability, winds, temperature, and precipitation.[9,10] We used the twice-daily upper-air data from the radiosonde station at the Metropolitan Oakland International Airport (OAK), which is the nearest upper-air station (approximately 55 km north-northwest of the model airport). For the seven-day modelling used in the model-to-monitor comparison, we used on-site hourly surface wind data collected concurrently with air concentration data. As described in Section 2.3, for the annual modeling, we used the 1-minute ASOS wind data and the hourly surface meteorological data from SJC (Norman Y. Mineta San Jose International Airport; SJC; WBAN ID 23293; approximately 10 km northwest of RHV). Review of the SJC ASOS station data showed its flow directions were similar to those measured concurrently at RHV, and sensitivity analyses showed that model performance using the SJC 1-minute wind data was equivalent to using the on-site monitored data for the seven days of monitoring data.

AERSURFACE Parameterization

AERMET requires three surface characteristics for the area around the study site (RHV) in order to estimate turbulence and mixing heights. These characteristics are albedo, Bowen ratio (ratio of sensible heating to latent heating), and surface roughness length. The AERSURFACE[11] preprocessor estimates these surface characteristics based on land cover and user inputs that describe the site and its climatology. Albedo and Bowen ratio values are calculated within 10

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[9] AERMOD: AERMIC Model, where AERMIC = American Meteorological Society/EPA Regulatory Model Improvement Committee.

[10] AERMET: AERMIC Meteorological Processor. Available: http://www.epa.gov/ttn/scram/metobsdata_procaccprogs.htm#aermet

[11] AERSURFACE: AERMOD Surface Characteristics Processor. Available: http://www.epa.gov/ttn/scram/dispersion_related.htm#aersurface

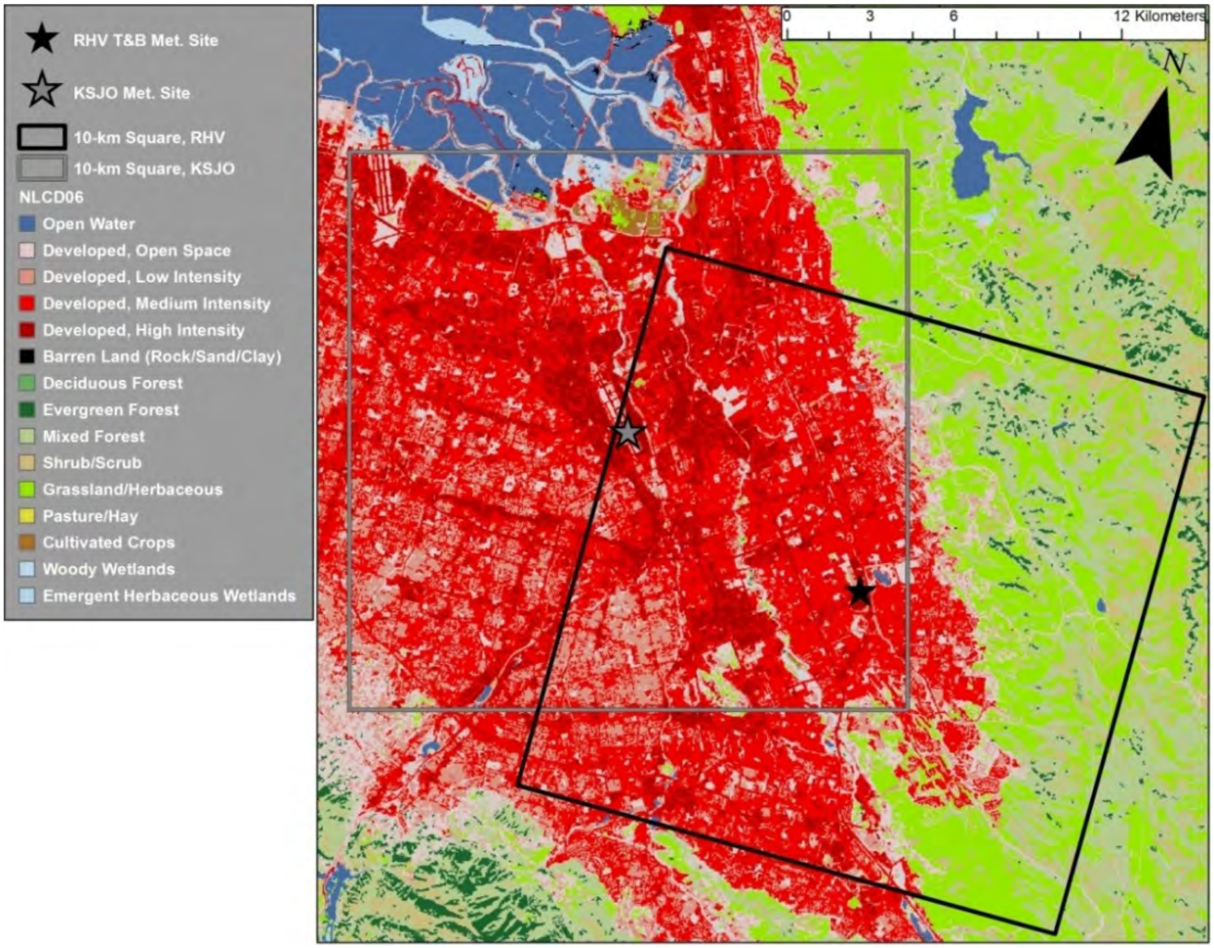
km of the study site, and 1 km is the recommended default radius for calculating surface roughness (USEPA 2008a, USEPA 2009).

While AERSURFACE only accepts version 1992 of the Multi-Resolution Land Characteristics Consortium (MRLC) and the National Land Cover Database (NLCD92), two more recent versions of the NLCD (2001 and 2006) are available. Between 1992 and the date of the most recent version, 2006, the proportion of land that was developed within 10 km of RHV increased approximately 15 percent[12], the developed land became more "intensely" developed,[13] and grasslands shrank. Reductions in grasslands and increases in development increase Bowen ratio (by up to 100-200 percent) and surface roughness (by up to two orders of magnitude), which lead to greater turbulence and higher mixing heights.

Given these important differences in land cover between 1992 and 2006, and given that the AERSURFACE only accepts NLCD92 data; Geographic Information Systems (GIS) software was used to reproduce the functionality of AERSURFACE while using NLCD06 data. For surface roughness lengths, land cover class fraction was determined within approximately 1 km of the meteorological site for each 30 degree wedge over 12 directional sectors. For simplicity, the 1-km distance was determined using a 1x1-km square centered on the meteorology site, so the distance was 1 km from the site perpendicularly to each side and approximately 1.4 km to each corner. For Bowen ratio and albedo calculations, the number of each land cover class was counted within a 10x10-km area centered on the meteorology site (the default area specified in (USEPA 2008a)). The land cover and 10x10-km squares for the model airport and the ASOS station site (SJC) are shown in Figure A-4.

[12] From approximately 56 percent to approximately 71 percent.

[13] The proportion of developed land that was medium- and high-intensity increased from approximately 18 percent in 1992 to approximately 66 percent in 2006.



Land Cover Image Source: National Land Cover Database http://www.mrlc.gov/nlcd2006.php

Figure A-4. The 10x10-km squares used to evaluate albedo and Bowen ratio, with NLCD06 base map

Next the surface characteristics were paired with the climate conditions (i.e., season definitions, wetness, and aridity) of each site based on 1981-2010 NCDC climate normal[14] data for SJC. Monthly season assignments were subjective and based on monthly average temperatures and precipitation. The aridity determination used annual average precipitation data (where the average annual rainfall at SJC is 15 inches). Wetness values were determined by comparing monthly precipitation data to the climate normal monthly precipitation data, where months receiving less than half the normal precipitation amount were considered dry and months receiving over twice the normal precipitation amount were considered wet. Monthly climate statistics at SJC are shown in Table A-7.

[14] Climate normals are the three-decade averages of climatological variables including temperature and precipitation. These are updated every ten years with the most current period from 1981-2010. Available: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca7821

Table A-7. Monthly climate statistics at the SJC ASOS Station

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TEMPERATURE (F): 30-year normal	50.1	53.3	56.2	58.9	63.4	67.5	70.0	70.1	68.5	63.2	55.1	50.0
PRECIPITATION (in.): 30-year normal	3.07	3.11	2.54	1.18	0.51	0.10	0.02	0.02	0.18	0.80	1.68	2.61
SEASON ASSIGNMENT FOR ALL MODELING:	**Fall**	**Fall**	**Spring**	**Spring**	**Sum.**	**Sum.**	**Sum.**	**Sum.**	**Sum.**	**Sum.**	**Fall**	**Fall**
PRECIPITATION (in.): 2010	4.58	2.12	1.94	3.10	0.35	0	0	0	0	0.02	1.76	2.58
PRECIPITATION (in.): Ratio 2010 to 30-year normal for month	1.49	0.68	0.76	2.63	0.69	0	0	0	0	0.03	1.05	0.99
WETNESS ASSIGNMENTS	**AVG**	**AVG**	**AVG**	**WET**	**AVG**	**DRY**	**DRY**	**DRY**	**DRY**	**DRY**	**AVG**	**AVG**
PRECIPITATION (in.): 2011	--	--	--	--	--	--	--	0	--	--	--	--
PRECIPITATION (in.): Ratio 2011 to 30-year normal	--	--	--	--	--	--	--	0	--	--	--	--

[a] Color shading is arbitrary and is for visualization purposes only.

Finally, the above information was combined with the surface characteristic lookup tables (USEPA 2008a), to report the surface characteristics at each site by month and sector (the latter only for surface roughness length). The values of albedo and Bowen ratio are shown in Table A-8 for the on-site meteorology at the model airport (only for August 2011, as used in the model-to-monitor comparison) and for the meteorology site at SJC (for 2010, as used in the annual modeling). The albedo is 0.17 at both sites, reflecting the predominantly residential land cover within 10 km of both sites. The Bowen ratio values vary by the season and wetness value determination, from 0.78 to 2.42 (with 2.07 the August 2011 value at the model airport).

Table A-8. Albedo and Bowen ratio values within approximately 10 km of the meteorology sites

Met. Site	Month	Albedo	Bowen Ratio
T&B at model airport (year 2011)	8	0.17	2.07
SJC (year 2010)	1	0.17	1.24

Met. Site	Month	Albedo	Bowen Ratio
	2		1.24
	3		1.12
	4		0.78
	5		1.15
	6		2.42
	7		2.42
	8		2.42
	9		2.42
	10		2.42
	11		1.24
	12		1.24

After completing the 2010 modeling results, it was discovered that the 1- and 10-km squares used at the SJC site were not oriented in a typical north-south alignment but were rotated approximately 18^{o} counterclockwise from the north. Rotating to a north-south alignment had no effect on albedo values. On average, the Bowen ratio values were 6 percent larger than if the area was oriented north-south—this is mostly because the north-south alignment encompassed less open water and more developed land compared to the rotated square. The effect of the rotation on surface roughness length values was mixed. Compared to the values using the north-south alignment, roughness length values were unaffected for most or all months in two sectors (the 60-90 and 150-180 degree sectors), were an average of 8 percent or 4 cm smaller for all months in six sectors (the 0-30, 90-120, 210-240, 240-270, 300-330, and 330-360-degree sectors), and were an average of 13 percent or 5 cm too large for all months in 4 sectors (the 30-60, 120-150, 180-210, and 270-330 degree sectors). The sectors that have the largest impact on the modeling results, in terms of dominant wind directions, are the 90-120, 120-150, and especially the 270-300 and 300-330 degree sectors. On average during airport operation hours, the cumulative effect of this rotation was to raise the mixing height by less than 1 percent (less than 5 m), with similarly small positive or negative effects on sensible heat flux, surface friction velocity, convective velocity scale, and stability. Test runs in AERMOD suggested that these differences would have no more than a 1-percent effect on 3-month average modeled air concentrations and depositions.

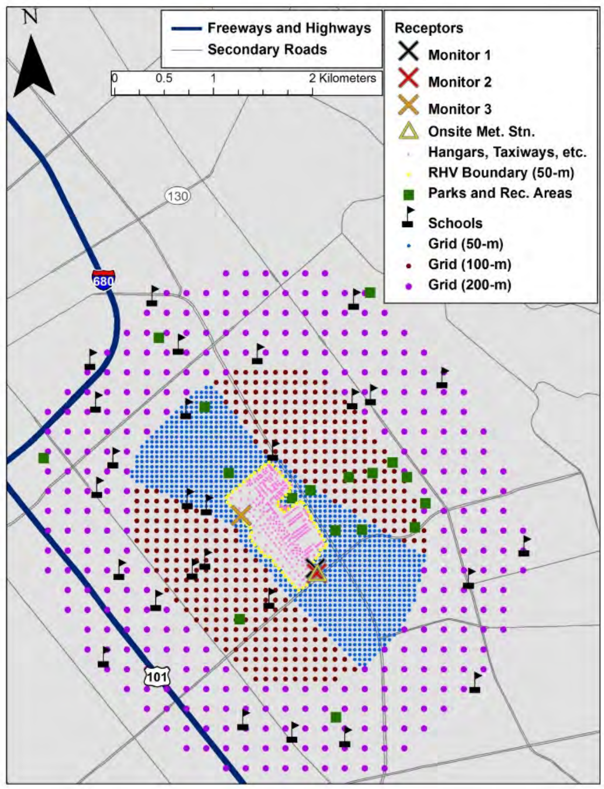
Urban Setting

Urban boundary layers were parameterized with AERMOD's urban setting option, along with the estimated 2009 population of the local area, Santa Clara County (1,785,000).[15]

[15] At the time of this development the 2010 census data had not yet been released. Subsequently, the 2010 census has become available and the reported total population of Santa Clara County was 1,781,642. Available: http://www.census.gov

A.1.4 Receptors

To fully define the spatial extent of elevated lead concentrations within the vicinity of the airport, 2,250 receptor locations were used, as shown in Figure A-5. Also shown are the locations of the three ambient air monitoring stations. Inside the airport property and around the airport boundary, receptors were placed at 50 m intervals, with approximately 365 receptors placed across the airport on taxiways, airport hangars, access roadways, buildings, and the airport meteorology station. Beyond the airport boundary, the 50 m grid spacing continued along the northwest-southeast orientation axis which is parallel to the runways; for the other areas within 1 km of the facility boundary a 100 m grid spacing was implemented; for areas out to 2 km, 200 m grid spacing was implemented.



Road Image Source: ESRI U.S. Major Roads version 9.3.1

Figure A-5. Receptor field for ambient air quality concentration analysis

A.1.5 Emission Source Characterization and Parameters

Aircraft

We modeled aircraft as volume sources within AERMOD, which is the method recommended by EPA for modeling a “line source” representing a moving object (USEPA 2004), and is the same approach used in previous air quality modeling at a general aviation airport (USEPA 2010, Carr et al. 2011). The modeled coordinates and release heights above the surface represent the center of the volume. The equations below, as shown in Table A-9, were used to calculate initial sigma-y and sigma-z values (horizontal and vertical plume extents).

$$\text{Sigma} - \text{z}(m) = \left[1.8 + \left(0.11 \times \frac{W2}{U}\right)\right] \times \left(\frac{60}{30}\right)^{0.2}$$ (Equation A-3)[16]

$$\text{Sigma} - \text{z}(m) = F + G + \text{Eq. A-3}$$ (Equation A-4)[17]

$$\text{Sigma} - \text{y or z}(m) = \frac{A}{B}$$ (Equation A-5)[18]

$$\text{Sigma} - \text{y}(m) = C + D + E$$ (Equation A-6)[19]

Table A-9. Sigma-y and sigma-z values of modeled aircraft volume sources

LTO	Sigma-y (m)	Sigma-z (m)
Taxi	23.26 Used Eq. A-5 where: A = 50 m (horizontal spacing between source points); B = 2.15	2.64 Used Eq. A-3, where: W2 = 11.43 m (width of the wider taxiway (22.86) divided by 2); U = 2.54 m/s (mean wind speed during the modeling period during RHV operational hours)
Run-up	6.4 Used Eq. A-6, where: C = 4.96 m (typical wingspan (10.67 m) divided by 2.15); D = 0.6 m (horizontal momentum of the exhaust);[a] E = 0.85 m (propeller turbulence wake)[b]	3.48 Used Eq. A-4, where: F = 0.5 m (release height); G = 0.65 m (exhaust buoyancy);[c] W2 = 5.34 m (typical wingspan (10.67 m) divided by 2); U = 2.54 m/s (mean wind speed during the modeling period during RHV operational hours)

[16] Benson, P. E. (1979). Abridged User's Guide for CALINE-3 - A versatile dispersion model for predicting air pollutant levels near highways and arterial streets. O. o. T. Laboratory. Section 5.2.

[17] USEPA (2010). *Development and Evaluation of an Air Quality Modeling Approach for Lead Emissions from Piston-Engine Aircraft Operating on Leaded Aviation Gasoline*. EPA-420-R-10-007. https://nepis.epa.gov/Exe/ZyPDF.cgi/P1007H4Q.PDF?Dockey=P1007H4Q.PDF ., Section 4.2, for the run-up mode of fixed-wing piston-fired aircraft.

[18] USEPA (2004). *User's guide for the AMS/EPA regulatory model - AERMOD*. Office of Air Quality Planning and Standards. September 2004. https://www3.epa.gov/ttn/scram/models/aermod/aermod_userguide.pdf ., Table 3-1, for either a single volume source or a line source represented by separated volume sources, depending on the LTO.

[19] USEPA (2010). *Development and Evaluation of an Air Quality Modeling Approach for Lead Emissions from Piston-Engine Aircraft Operating on Leaded Aviation Gasoline*. EPA-420-R-10-007. https://nepis.epa.gov/Exe/ZyPDF.cgi/P1007H4Q.PDF?Dockey=P1007H4Q.PDF . Section 4.2

LTO	Sigma-y (m)	Sigma-z (m)
Moving non-taxi (take-off, climb, approach, landing)	23.26 Used the same method as taxi (see above).	2.33 Used Eq. A-3, where: W2 = 5.34 m (typical wingspan (10.67 m) divided by 2); U = 2.54 m/s (mean wind speed during the modeling period during RHV operational hours)

[a] The 0.6 m horizontal exhaust momentum was based on a sensitivity test with SCREEN3 with and without the typical exhaust flow of 100 ft^3/min.
[b] The 0.85 m propeller turbulence wake was calculated by dividing the typical 1.83 m propeller size by 2.15.
[c] The 0.65 m exhaust buoyancy was based on a sensitivity test with SCREEN3 with and without an exhaust temperature of 573 K.

Point and Area Sources

SJC, a nearby airport, was modeled as an area source using the approximate airport boundary line, while all other data in the point source file were modeled as point sources. For the SJC area source, the North American Industrial Classification System (NAICS) code was used to identify the average release height from California lead emitters in the 2005 NEI v2, and this average release height was used in lieu of a sigma-z. For the point sources, the same NAICS methodology was used from the 2005 NEI v2 for release height, stack diameter, and exit gas temperature and velocity. All release heights were between 8 and 13 meters, stack diameters were less than 1 meters, exit gas temperatures were between 300 and 600 K, and exit gas velocities were between 5 and 25 m/s.

Nearby Road Sources

The lengths and widths of the area sources used to model nearby road sources were determined using aerial photos. A release height of 2 meters and an initial sigma-z of 2.15 m were applied to all roadways which accounts for the mix of light and heavy-duty vehicles as well as vehicle induced turbulence.

Gridded Area, On-Road Mobile, and Non-Road Mobile Sources

Consistent with previous air quality modeling at a General Aviation airport (USEPA 2010, Carr et al. 2011), gridded area, on-road mobile, and non-road mobile sources were modeled as area sources with a release height of 2 m and a sigma-z of 2.15 meters.

A.2 Sensitivity Analysis of Model-to-Monitor Comparison at the Model Airport

As discussed in Section 2.2 of the report, model-to-monitor comparisons at the model airport over a seven-day period showed modeled concentrations were well within a factor of two of monitored concentrations, which is a typical metric for robust model performance. The sensitivity analysis described in this section was conducted in order to evaluate key input parameters for their potential impact on modeled concentrations. Lead monitoring data also have uncertainty and variability that may contribute to differences between monitored and modeled concentrations.[20] This appendix presents information regarding only the modeling sensitivity analyses.

The sensitivity analyses focused on the subset of parameters that previous modeling suggested most strongly influence concentrations: 1) the location that pilots use for run-up activities, 2) the duration that pilots conduct run-up activities, and 3) whether pilots are using a SE- or ME plane.[21] Regarding the first parameter, run-up activities are conducted in a designated area immediately adjacent to a runway end; however, the area is generally large enough for several aircraft to park in, and thus the location of run-up relative to a monitor or model receptor can vary by several meters depending on where an aircraft is within the designated run-up area. Run-up activities that are modeled to occur closer to a model receptor than actually occurred, would be expected to result in the model over-predicting concentrations when compared with monitored concentrations. Conversely, run-up activity that is modeled to be further away from the location at which an aircraft conducted this activity would be expected to result in the model under-predicting concentrations compared with monitored data. To evaluate this distance parameter, a series of supplemental model receptors were setup in three concentric rings around the monitor adjacent to the maximum impact location on days with under- or over-prediction as shown in Figure A-6. The use of supplemental model receptors is analogous to moving the emissions source in the model (i.e., aircraft conducting run-up), but is more feasible (i.e., requires less modifications to the model runs and can be completed in a single model run).

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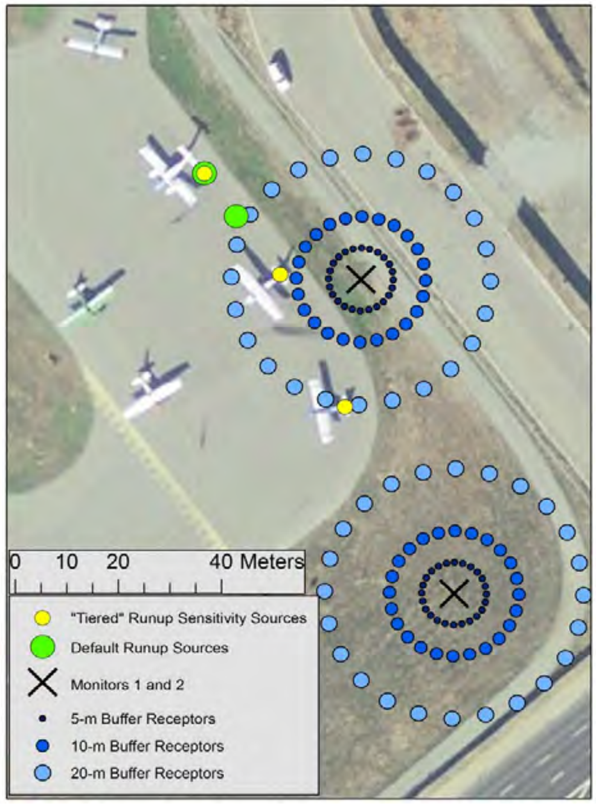
[20] EPA's Data Quality Objective Goals for lead is defined as follows: Measurement quality objectives for precision will be 20% for a 90% confidence limit coefficient of variation and an overall absolute bias upper bound goal of 15%. Goals will be assessed on 3 years of data at the PQAO level of aggregation. EPA-545/B-14-002 September 2014. Available at: https://www3.epa.gov/ttnamti1/files/ambient/pb/PbPEPHighVolumeSamplingSOP2014Revision.pdf

[21] The concentration of lead in avgas is also a key parameter impacting ground-level concentrations of lead. The concentration of lead in fuel supplied at RHV during this time period was analyzed and found to be slightly higher than the maximum specification for avgas and is therefore considered the highest concentration likely. The analytical value determined for avgas supplied at RHV was used in the air quality modeling and a sensitivity analysis was not conducted. It is possible that aircraft had fueled at other airfields and the lead content in the avgas being burned at RHV could have been lower than the maximum specification, potentially accounting for cases in which the modeled lead concentration over-estimated the monitored value.



Satellite Image Source: ESRI

Figure A-6 Concentric rings of receptors around two downwind monitoring locations

Regarding the second parameter, the duration of run-up varies from pilot to pilot. The median run-up observed at RHV was 40 and 63 seconds for SE and ME aircraft, respectively. These median run-up times were used to develop modeled concentrations for SE and ME; however, the 5th and 95th percentiles of run-up times were 16 and 121 seconds for SE aircraft, or 16 and 160 seconds for ME aircraft at RHV.[22] If one or more pilots run-up for longer or shorter periods than the median used in modeling, then modeled concentrations could over- or under-predict monitored concentrations, respectively.

Finally, the third parameter of SE versus ME activity can influence modeled concentrations based on the fact that ME aircraft have higher fuel consumption due to the fact that ME aircraft have two, or more, engines rather than the one engine of a SE aircraft. As such, more ME activity than included in the modeling for a given day could result in model over-prediction, while fewer ME aircraft conducing run-up could result in model under-prediction.

All three parameters were examined for days during which the model over- or under-predicted monitored concentrations. On the one day of over-predication, shifting the run-up location (i.e., using supplemental model receptors) to a more southerly run-up location, which was further from the maximum impact location monitor, resulted in the median value of concentrations at

[22] The distributions of run-up duration at the model airport and at other airports are shown in Appendix C.

supplemental model receptors falling just below the monitored concentrations, such that the monitored value was within the third quartile of supplemental receptor concentrations (Figure A-7). The remaining difference between modeled and monitored concentrations could result from less ME aircraft activity occurring on this day than was recorded by observers, or from shorter than median run-up durations. While other parameters could contribute to some of the remaining difference between monitor and modeled concentrations, this evaluation focused on those parameters shown to most strongly impact concentrations.

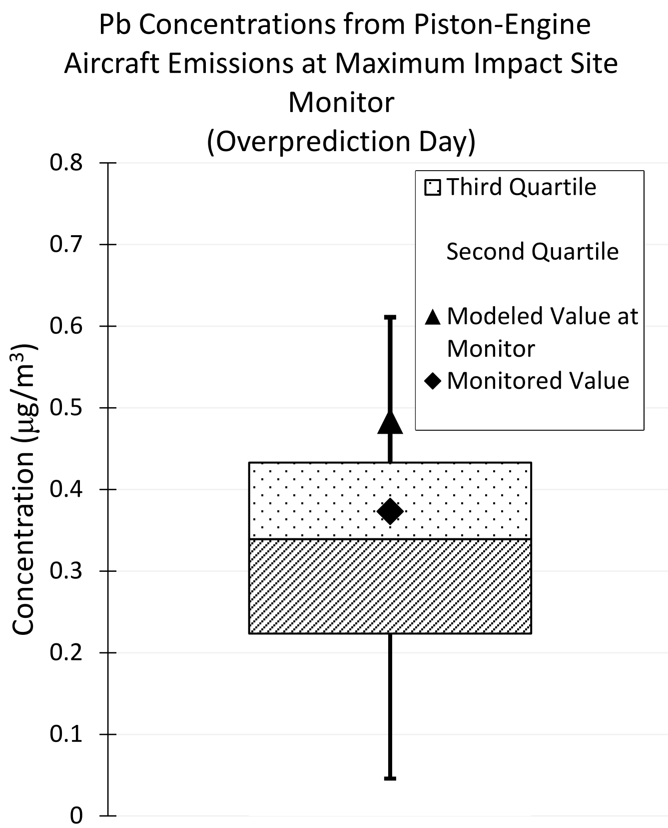


Figure A-7. Range of modeled lead concentrations from piston-engine aircraft during airport operating hours at supplemental receptor sites on day that model over-predicted monitored concentrations. Whiskers represent first and fourth quartiles. Supplemental model receptors were placed in concentric circles of 5, 10, and 20 meters from the monitor to mimic a change in run-up location.

Figure A-8 presents the range of concentrations at the supplemental model receptors on one of the days that the modeled lead concentration under-predicted the monitored concentration. The range in concentrations at supplemental model receptor sites still falls below the monitored concentration, suggesting that a shift in run-up location did not account for the difference in concentrations. Longer run-up time and higher fuel consumption on this particular day (compared with the median observed at the model airport) are possible explanations for the difference between modeled and monitored concentrations. Thirty-percent of the difference in concentrations would be accounted for if 10% of pilots conducted run-up for 2 mins, as opposed to the 40 or 63 second median values for single- or multi-engine aircraft, respectively. This combined with higher levels of ME activity (i.e., higher fuel consumption) could result in a modeled concentration much closer to the monitored value, similar to model performance on the majority of model to monitor comparison days.

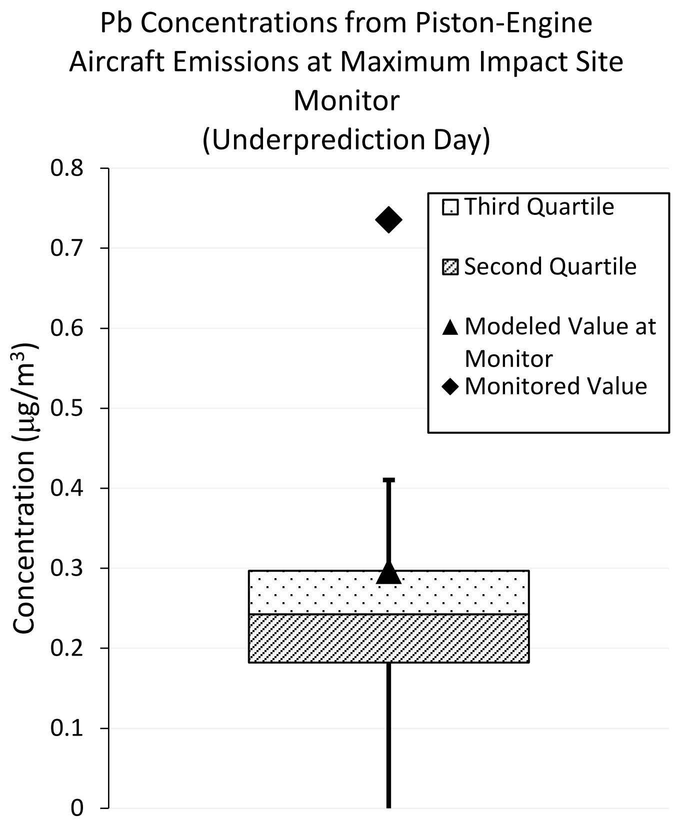


Figure A-8. Range of lead concentrations from piston-engine aircraft during airport operating hours at supplemental receptor sites on one day that the model under-predicted monitored concentrations. Whiskers represent first and fourth quartiles. Supplemental model receptors were placed in concentric circles of 5, 10, and 20 meters from the monitor to mimic a change in run-up location.

Another possible cause for the underestimation of the modeled concentration is a possible overestimate of the initial sigma-y and initial sigma-z. As described in Section A.1, we used an average wingspan of 10.67 m (35 feet) for our initial sigma-y and sigma-z calculation. If the average aircraft wingspan is smaller, then the initial lateral and vertical dispersion may be overestimated, leading to an underestimate of the peak concentration.

One additional factor of note is a challenge commonly faced when modeling mobile source emissions, namely modeling concentrations closely proximate to the emission source can result in receptors being placed within the modeling exclusion zone. The exclusion zone is the region

2.15 X sigma-y + 1 meter from the center of the volume source. When the source is parameterized as a volume source (the approach used for aircraft emissions in this work), AERMOD reports concentrations of zero for receptors that are inside the exclusion zone of that particular volume source. This results in concentrations that are biased low. In the sensitivity analysis presented here, several receptors were within the exclusion zone and, therefore, the concentration of lead reported at these receptors is biased low. Note that for the year-long modeling analysis presented in Section A.1, there were no receptors inside the exclusion zone.

A.3 Fleet Composition Between the Model Airport and the National Fleet

Section A.3 presents an evaluation of two key parameters that underlie the development of the AQFs (as presented in Section 3 of the report) in order to understand similarities and differences between piston-engine aircraft operating at the model airport and those in the national fleet. Specifically, this appendix compares the aircraft classes and engine types active at the model airport to a national database of registered piston-engine aircraft since fuel consumption rates differ across aircraft class and engine type which in turn impacts lead concentrations. As described in Section 2 of the report, AQFs were developed using modeled concentrations at a model general aviation airport. As input to the air quality model, aircraft were observed at the model airport for a period of ten days. The counts of unique aircraft by aircraft class (SE/ME) and engine type were then compared to a national database of all US registered piston-engine aircraft. Of the 403 piston aircraft observed at the model airport, 377 (92.0%) were single-engine aircraft. In the national registered piston database, 225,697 of 245,665 (91.9%) aircraft were single-engine. Thus, the differences in the aircraft class populations are not statistically significant (χ^2 =1.617, p = 0.2035).

Tables A-10 and A-11 present the total number of piston aircraft organized by engine technology group (4-stroke horizontal carbureted [carb], 4-stroke horizontal fuel injected [fi], 4-stroke horizontal spark turbocharged [turbo], and 2-stroke horizontal) and horsepower for the national database of registered piston aircraft and the observed aircraft at the model airport. Aircraft were categorized as ‘Missing’ where either engine technology type or engine size data was unavailable. Radial engines are not presented in Tables A-10 and A-11 as they span a broader range of horsepower, but account for only 3.6% and 2.5% of engines in the national database and observed at the model airport, respectively.

Table A-10. Number of piston-engine aircraft in the national fleet by technology group and horsepower

Tech. Group	Horsepower (hp)									
	hp<100	100≤hp <150	150≤hp <200	200≤hp <250	250≤hp <300	300≤hp <350	350≤hp <400	400≤hp <450	450≤hp	Total
4-Stroke Carb.	28,137	34,110	51,675	17,650	8,771	1,116	46	874	243	142,722
4-Stroke FI	15	405	12,035	5,502	16,889	12,099	125	152	0	47,225

Tech. Group	Horsepower (hp)									
	hp<100	100≤hp <150	150≤hp <200	200≤hp <250	250≤hp <300	300≤hp <350	350≤hp <400	400≤hp <450	450≤hp	Total
4-Stroke Turbo	17	320	130	2,694	980	11,980	448	67	185	16,921
2-Stroke	2,566	17	0	0	61	0	0	0	0	2,644
Missing = 27,769										

Table A-11. Number of piston-engine aircraft in the model airport fleet by technology group and horsepower

Tech. Group	Horsepower (hp)									
	hp<100	100≤hp <150	150≤hp <200	200≤hp <250	250≤hp <300	300≤hp <350	350≤hp <400	400≤hp <450	450≤hp	Total
4-Stroke Carb.	17	51	93	34	12	2	0	1	0	210
4-Stroke FI	0	0	33	9	37	26	0	0	0	105
4-Stroke Turbo	0	0	0	6	1	28	1	0	0	36
2-Stroke	1	0	0	0	0	0	0	0	0	1
Missing = 42										

Due to the small number of observations for several horsepower groups, comparisons of engine power at the model airport and in the national fleet were difficult. Pearson's Exact Tests comparing engine powers at 50 horsepower intervals showed no statistically significant differences at the 5% significance level between the model airport and the national database. A broader comparison of engines across the five technology groups at the model airport versus the national database did show a difference in fleet composition, which is statistically significant 5% level (χ^2 =15.83, p = 0.0012). However, in general, the distributions are similar by each technology group and for each engine horsepower rating. In particular, the most common engine category in the national fleet, 4-stroke carbureted engines between 150 and 200 hp, is also the most common engine category observed at the model airport.

Comparing across engine technology groups further identifies similarities between aircraft at the model airport and the national fleet. Table A-12 shows the total observed engine counts at the model airport for all technology groups and compares these totals to the fleet that would be expected if there was absolute parity in the engine distribution between the model airport and the national database. Table A-3 excludes missing data from the observations at the model airport and the national fleet database. The rank order and relative magnitude of technology group prevalence is the same in the observed fleet and the expected fleet from the national aircraft database. The model airport, however, has fewer observed carbureted engines than predicted and more fuel injected and turbocharged engines than predicted. Because fuel-injected engines are generally more fuel efficient and turbocharged engines are generally less fuel efficient than carbureted engines (Heiken et al. 2014), there is an expectation that any high or low bias in fuel consumption from the high prevalence of one of these engine technology types would be offset by the similar high prevalence of the other. In addition, the prevalence of fuel injected and turbocharged engines across the 10 survey days suggest that these engine technology groups may make up a slightly disproportionate percentage of total operations at the model airport compared to the national fleet. Importantly, due to the fact that not all aircraft registered in the national database may be routinely operated, differences between the observed aircraft operating at the model airport and aircraft in the registered database may not be indicative of differences between aircraft operating at the model airport and aircraft operating at other airports. Overall, results suggest that differences between the observed fleet at the model airport and the national piston-engine aircraft fleet generally balance out (i.e., turbocharged versus fuel-injected), or are not statistically significant.

Table A-12. Fleet composition by aircraft engine technology

Engine Technology Group	Model Airport Composition	National Fleet Composition	Observed Aircraft at Model Airport	Expected Aircraft at Model Airport Given National Composition
4-Stroke, Carbureted	58.1%	65.7%	210	237
4-Stroke, Fuel Injected	29.1%	21.7%	105	79
4-Stroke, Turbocharged	10.0%	7.8%	36	28
2-Stroke	0.3%	1.2%	1	4
4-Stroke Radial	2.5%	3.6%	9	13

A.4 Mode-Specific Fuel Consumption

In the air quality modeling approach used to develop AQFs, total fuel consumption was modeled using engine-specific fuel consumption rates for 18 engine types. The 18 engine types span the five engine technology groups (4-stroke horizontal carbureted, 4-stroke horizontal fuel injected, 4-stroke horizontal turbocharged, 4-stroke radial, and 2-stroke horizontal) for piston-engine spark ignition aircraft engines and range from 64-575 horsepower. For each engine type, fuel consumption rates were prescribed for each landing-and-take-off (LTO) mode based on the FAA's Emission and Dispersion Modeling System (EDMS) Version 5.0.2 or the Swiss Federal Office of Civil Aviation (SFOCA), "Aircraft Piston Engine Emissions Summary Report" supporting data (FAA 2007, SFOCA 2007).

The approach laid out in Heiken, et al., 2014 included calculating fuel consumption by using default brake specific fuel consumption (BSFC) rates for each of the five spark ignition piston-driven aircraft engine technology groups (Heiken et al. 2014). BSFC is the mass of fuel consumed per unit work done by the engine and is a measure of engine efficiency. BSFC data for each LTO mode for 29 unique engines were compiled from several sources including the FAA's EDMS model and the SFOCA piston engine summary report. Where BSFC data were not available for a LTO mode for an engine, mode-specific BSFC were estimated by applying a scaling factor to the takeoff BSFC for that engine. Engines were sorted by technology group, and the default mode-specific BSFCs were taken as the mean BSFC for each technology group and LTO mode.

A comparison between the resulting fuel consumption rates used to characterize lead concentrations at the model airport (labeled as MA Fuel Consumption) and in Heiken et al., 2014 (labeled as Heiken Fuel Consumption) is shown in Figure A-9. For each LTO mode, the fuel consumption rate for each of the 18 engines used in the AQF approach is plotted against the fuel consumption rate that would be assumed for an identical engine using the mode-specific default BSFC approach.

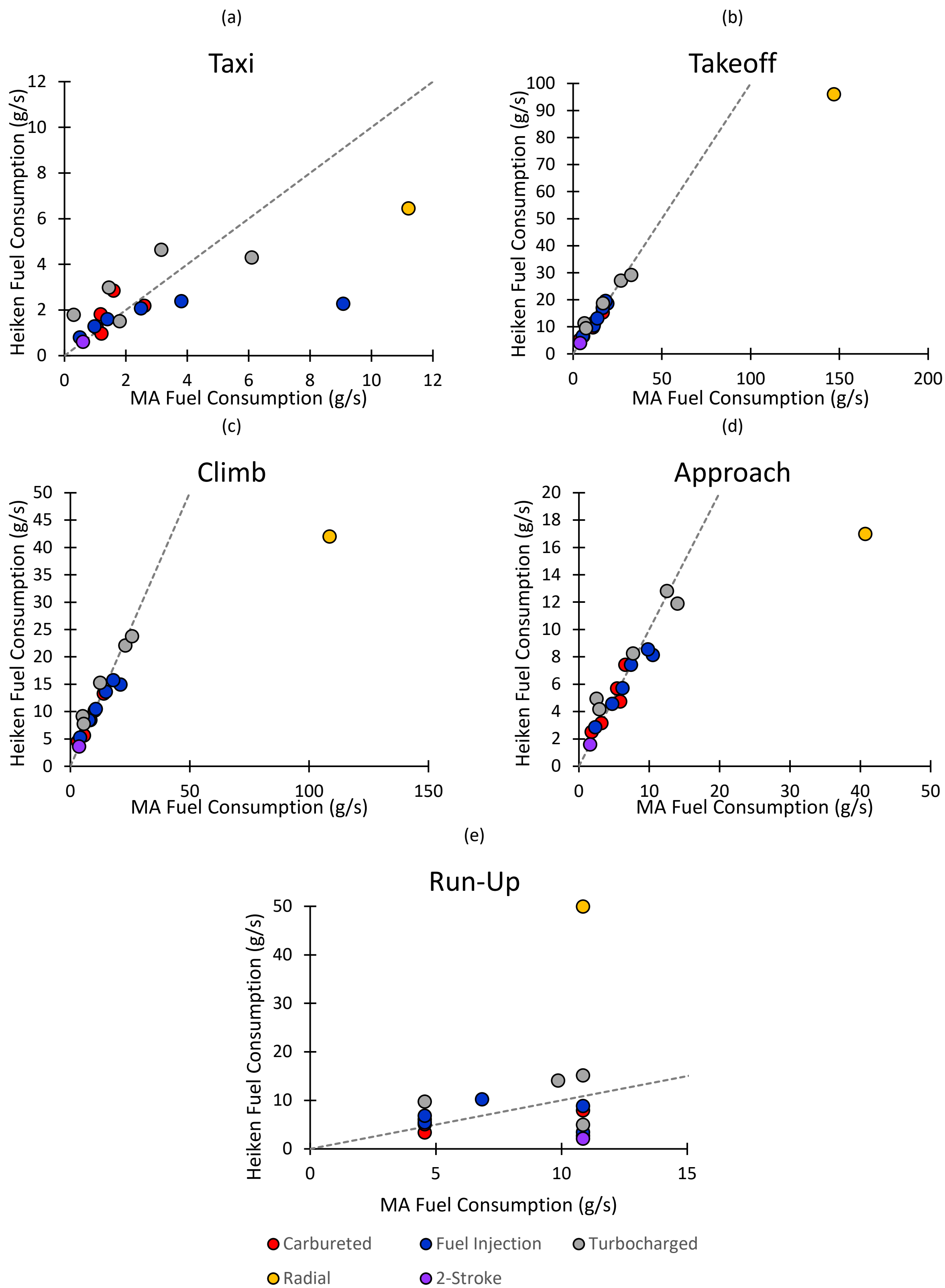


Figure A-9. Fuel consumption rates by engine technology group and LTO mode (Heiken et al. 2014)

For taxi, takeoff, climb, and approach modes, fuel consumption rates between the two studies strongly correlate (R = 0.993 for takeoff to R = 0.745 for taxi). For each of these modes, a single radial engine was an outlier with model airport fuel consumption greater than the fuel consumption rate reported by Heiken et al. Two radial engines were in the database used to determine the radial engine default BSFC in Heiken et al. one (Wright R-1820) with similarly high fuel consumption rates to the single engine value used in the model airport fuel consumption database and one radial engine with an undisclosed manufacturer and model number. Averaging the mode-specific BSFC across the two radial engines results in significantly lower predicted fuel consumption rates. Thus, using the default BSFC methodology from Heiken et al. may under-predict fuel consumption rates by not accounting for engine-to-engine variation within an engine technology group. Notably, the impact of the radial engine fuel consumption modeling assumption on resulting lead concentrations is expected to be small as radial engine aircraft account for only 3.6% of the national piston aircraft fleet.

Aircraft run-up fuel consumption rate data is sparser than data for other LTO modes. For the model airport, fuel consumption rates for the run-up mode were taken directly from EDMS and SFOCA where available. Only 4 unique run-up fuel consumption rates were identified. In the approach used in Heiken et al. run-up fuel consumption rate was defined as 52% of the maximum fuel consumption rate based on a survey of seven engine manuals that suggested individual run-up fuel consumption rates range from 43-68% of the maximum fuel consumption rate. Despite the lack of granularity in data, the models still show weak to moderate correlation (R^2 = 0.28). Fuel consumption rates used at the model airport were higher than those reported by Heiken et al. for 2-stroke carbureted engines and engines less than 100 horsepower. Aircraft with these engines account for less than 3% of the national piston aircraft fleet, as seen in Table A-10. In contrast, relative to the Heiken et al. approach, the data used at the model airport generally underestimates run-up fuel consumption rates for 4-stroke horizontal engines greater than 200 horsepower, about 24% of the national piston fleet. The fuel consumption rate for the radial engine is again an outlier; however, where higher estimates of radial engine fuel consumption rates were reported for other LTO modes, the run-up fuel consumption rate used for this engine at the model airport was lower than the fuel consumption rate relative to the Heiken et al. study. Overall, while methods used to calculate fuel consumption rates differ between the two studies, a comparison of the resulting rates suggest that the values are largely similar for modes other than run-up. Within the run-up mode, the results are moderately consistent, but there is more variability in the results compared with other modes of operation. Additional data would be necessary to further characterize and evaluate fuel consumption rates during the run-up mode for piston-engine aircraft.

A.5 Wind Speed Adjustment Methodology

Meteorological, geographical, and operational parameters may vary from conditions at the model airport or from the national default parameters used in the national analysis. Wind speed is one meteorological parameter that effects local concentration profiles of atmospheric aerosols. Specifically, the near-field concentration of a non-reactive passive tracer scales with $<\boldsymbol{u}^{-1}>$, where ***u*** is wind speed and angled brackets imply a time average (Barrett and Britter 2008). Thus, the model-extrapolated concentrations at and downwind of the maximum impact site can be adjusted to better consider meteorological conditions at individual airports by using inverse wind speed data over the 3-month maximum period. The methodology for deriving and applying the wind-speed adjustment is described below.

If the wind speed at the model airport is ***v*** and the wind speed at a specific airport is ***u***, then the wind-adjusted concentration would be the model extrapolated concentration estimated by the methodology detailed in Section 3 of the main report multiplied by the ratio of average inverse wind speeds $<\mathbf{v}^{-1}>/<\mathbf{u}^{-1}>$. If the wind speed at the specific airport is, in general, higher than the wind speed at the model airport where the AQFs were derived, then $<\underline{\mathbf{v}}^{-1}>$ would be less than $<\boldsymbol{u}^{-1}>$ resulting in a lower concentration per unit of activity (i.e., 1 LTO) at the specific airport than the AQF.

The effect of the wind-adjusted AQF is demonstrated and validated using the model airport data. First, we evaluated the range of weighted 3-month AQFs versus the range of rolling 3-month, inverse wind speeds. As shown in Figure A-10, the average inverse wind speed for the average weighted AQF[23] is 0.426 s/m with 3-month average inverse wind speed ranging from 0.325 to 0.523 s/m.

[23] The 'weighted AQF' is a composite of the maximum SE (89%) and ME (11%) full AQF, thereby reflecting expected operational splits between SE and ME aircraft. The approach is valid and holds for each of the individual (SE/ME, full/T&G) AQFs.

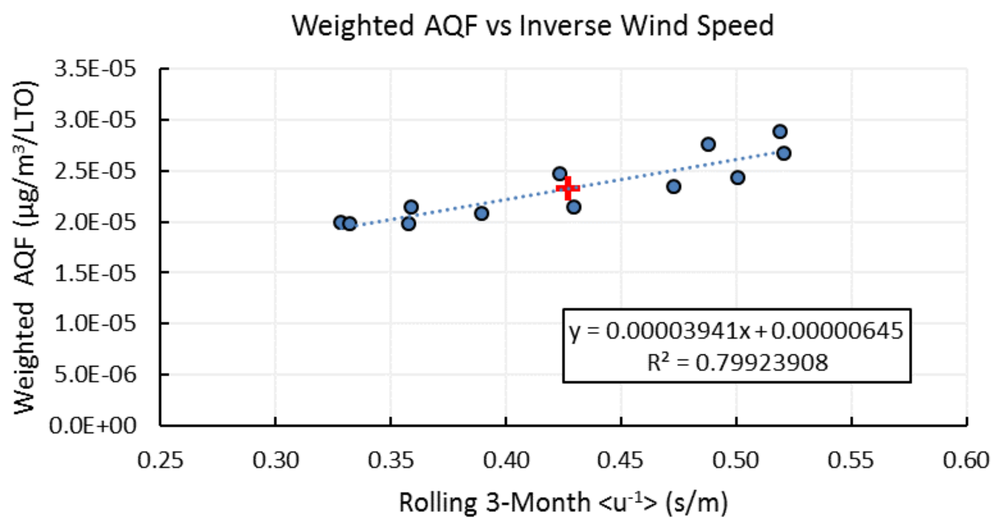


Figure A-10 Weighted AQF vs inverse wind speed for each 3-month rolling AQF at model airport

modeled, weighted AQF for each of the 3-month periods with the average AQF (or the AQF applied in the main analysis without considering wind adjustment) and the wind-adjusted AQF. Figure A-11 shows that the average AQF is always within +/-20% of the specific 3-month average modeled AQF. The wind-adjusted AQF performs even better, staying within 6% of the modeled AQF for all modeled periods.

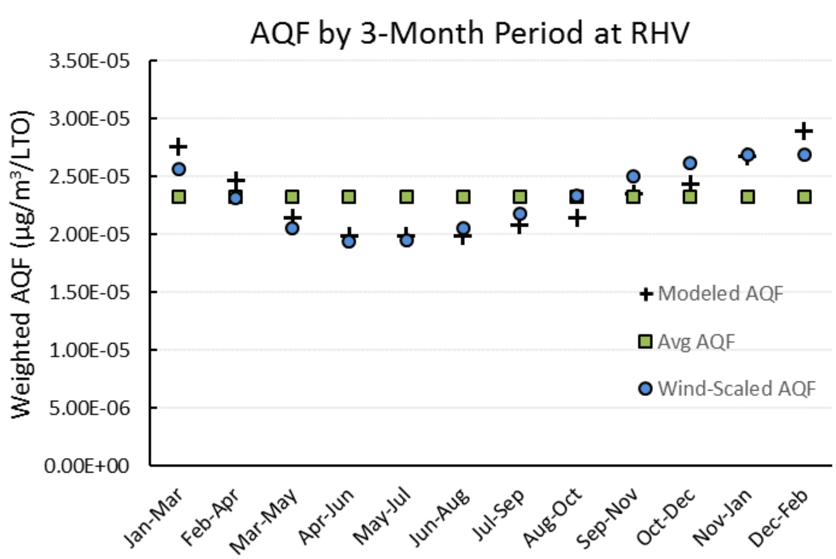


Figure A-11 Modeled, average, and wind-scaled AQF for each 3-month period

Utilizing the same wind data that was used to assign operations to specific runways, model-extrapolated concentrations at airports nationwide can be adjusted for wind-speed, thereby appropriately characterizing concentrations at airports with significantly higher or lower wind speeds than the model airport. For the wind speed adjustment, wind speeds from 6am to 11pm[24] are averaged over the entire year at the model airport and for the 3-month maximum activity period at the model airport. As the inverse of wind speed tends toward infinity as wind speed tends toward zero, 0.5 m/s is chosen as a minimum allowable wind speed to account for ASOS station wind detection limits.

[24] These are the modeled hours from opening through one hour past closing for each airport, reflecting the times when atmospheric lead concentrations are expected to be highest.

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Appendix B: Supplemental Data for Piston-Engine Aircraft Activity and Model-Extrapolated Lead Contraction Gradients

This appendix provides supplemental information on data sources and their application in methods detailed in Section 3 of the main report, which characterizes 3-month average model-extrapolated lead concentrations at and downwind of the maximum impact site for the runway-end with the most piston-engine aircraft activity in a 3-month period for airports nationwide. Section B.1 briefly describes the sources of airport activity data noting the extent of the data, its resolution, the data collection method, and the location of publicly available information. Section B.2 provides a detailed description of the diurnal profile used in the national and airport-specific activity analyses (Sections 3.2 and 3.3 of the main report); this profile is based on observations at the representative airport facility and is utilized in the AQFs presented in Section 3.1 of the main report. Section B.3 describes in detail the method for assigning operations to a specific runway using hourly wind data. Section B.4 provides the detailed aircraft and operational data for six airports where airport-specific data was available, which was utilized in Sections 3.3 and 4 of the main report. Section B.5 discusses piston-engine rotorcraft activity and provides information to support future analyses.

B.1 Airport Operations Data Sources

FAA provides a number of data sources related to aircraft activity at airports. The data sources relevant to this report are presented below and generally organized from the most to least detailed. As a reference, Table B-1 lists of FAA location identifiers (LID) with airport names and locations for airports identified by FAA LID in this report.

Table B-1. List of FAA location identifiers, airport names, and location by state/territory for airports identified in this report.

FAA LID	Airport Name	Location
52F	Northwest Regional Airport	TX
ORS	Orcas Island Airport	WA
RHV	Reid-Hillview Airport	CA
WHP	Whiteman Airport	CA

Air Traffic Activity System (ATADS)[1]

The Air Traffic Activity [Data] System (ATADS) contains the official National Airspace System air traffic operations data available for public release.[2] Approximately 500 US airports have either an FAA air traffic control tower or an FAA contract tower. ATADS provides daily operational data at the airport as reported by the control tower categorized by itinerant and local operations and separated by air carrier, air taxi, general aviation, and military. ATADS is updated monthly. While ATADS activity data is the most up-to-date and offers the finest temporal resolution of the FAA datasets, it is only available at the approximately 500 towered airports and does not specify activity by engine-type (e.g., piston- vs. jet-engine activity) within general aviation and air taxi.

National Plan of Integrated Airport Systems

The National Plan of Integrated Airport Systems (NPIAS) identifies nearly 3,400 existing and proposed airports that the FAA considers significant to national air transportation and are thus eligible to receive Federal grants under the Airport Improvement Program. The NPIAS includes all ATADS airports. Because these airports are eligible to receive Federal grants, they are subject to data reporting requirements, including reporting based-aircraft by tail number.

Terminal Area Forecast

The Terminal Area Forecast (TAF) is the official FAA forecast of aviation activity for US airports. Yearly reports detail historical annual activity data and projected operations for future years at the airport level for NPIAS airports.[3] The TAF also provides data and future projections of based aircraft for NPIAS airports.

FAA 5010 Report (Airport Master Record)

An Airport Master Record (Form 5010) is an electronically generated file for each airport facility that details General Information, including ownership, management, and location data; Services & Facilities including available fuel types and flight services; Based Aircraft & Operations; Runway Information; and Remarks, including special instructions and updates. A complete Form 5010 can be generated for an individual airport through the online AirportIQ DataCenter.[4]

The FAA Office of Airport Safety & Standards (AAS-100) provides access to airport facilities and runway data from Form 5010 for all public-use and private-use facilities (including ATADS airports, non-ATADS NPIAS airports, and non-NPIAS airports) available for download through the FAA website.[5] Based aircraft counts and annual activity levels are available through the Airport Facilities Data database. Operations data is reported for 12-month periods and are partitioned by Air Carrier, Air Taxi, General Aviation Local, General Aviation Itinerant, and Military. Operations at non-FAA airports are estimated by FAA inspectors or are based on

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[1] ATADS activity data and other operational data (such as delay) are now available through the FAA Operations Network (OPSNET). https://aspm.faa.gov/

[2] https://aspm.faa.gov/opsnet/sys/Main.asp

[3] https://aspm.faa.gov/main/taf.asp

[4] https://www.airportiq5010.com/5010web/

[5] https://www.faa.gov/airports/airport_safety/airportdata_5010/

information provided by airport managers, state aviation activity surveys, or other sources. Airport location and runway orientation are available through the Airport Runways Data database.

Airport data in the 5010 report is derived from the National Airspace System Resources Database (NASR). The NASR Database contains extensive aeronautical information on all US airports including safety critical data, navigational aid data, and airport configuration data. The NASR is updated every 56 days. The NASR Database is provided by the FAA's Aeronautical Information Services Group (AJV-5) through the National Flight Data Center (NFDC).[6] The NFDC is responsible for the collection, validation, and quality control of aeronautical information detailing the physical description, geographical position, and operational characteristics of airport facilities.

General Aviation and Part 135 Activity Survey/General Aviation and Air Taxi Activity (GAATA) Surveys

The General Aviation and Part 135 Activity Survey, also known as the General Aviation and Air Taxi Activity Survey (GAATA), is an annual data report produced from surveys of US pilots. The GAATA enables the FAA to monitor the general aviation fleet for purposes of anticipating and meeting demand, evaluating initiatives and regulatory changes, and measuring the safety of the GA community. The GAATA provides data as to the composition of the general aviation and air taxi fleet, including national data on fleet composition and operational hours by type of aircraft (e.g. piston-driven, turboprop, turbojet) and aircraft class (i.e. SE vs ME). The data collected are also used by other government agencies, the general aviation industry, trade associations, and private businesses to pinpoint safety problems and to form the basis for critical research and analysis of general aviation issues. Tabular data from annual GAATA reports are publicly available for download on the FAA website.[7]

General Aviation Manufacturers Association (GAMA) Statistical Databook

GAMA is an international trade association representing more than 90 of the world's leading manufacturers of general aviation airplanes and rotorcraft, engines, avionics, components, and related services. GAMA publishes an annual statistical databook and an annual industry outlook, containing diverse data from operations at airports to sales. While the GAMA databook is not used as a primary data source for modeling in the main report, it is a useful tool for validating data assumptions, such as GA operation trends.

The trends in total piston operations over six years for a sample subset of the 50 most active GA airports, as listed in the General Aviation Statistical Databook (GAMA 2016), are taken from ATADS data and are shown in Figure B-1. The median year-on-year change in operations at the top 50 GA airports ranges from -4% to 4% for a given year, and the interquartile of airport year-on-year operational changes is between +/-10% for all years. However, individual airport year-on-year changes range from -25% to +44%.

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[6] https://nfdc.faa.gov/nfdcApps/

[7] https://www.faa.gov/data_research/aviation_data_statistics/general_aviation/

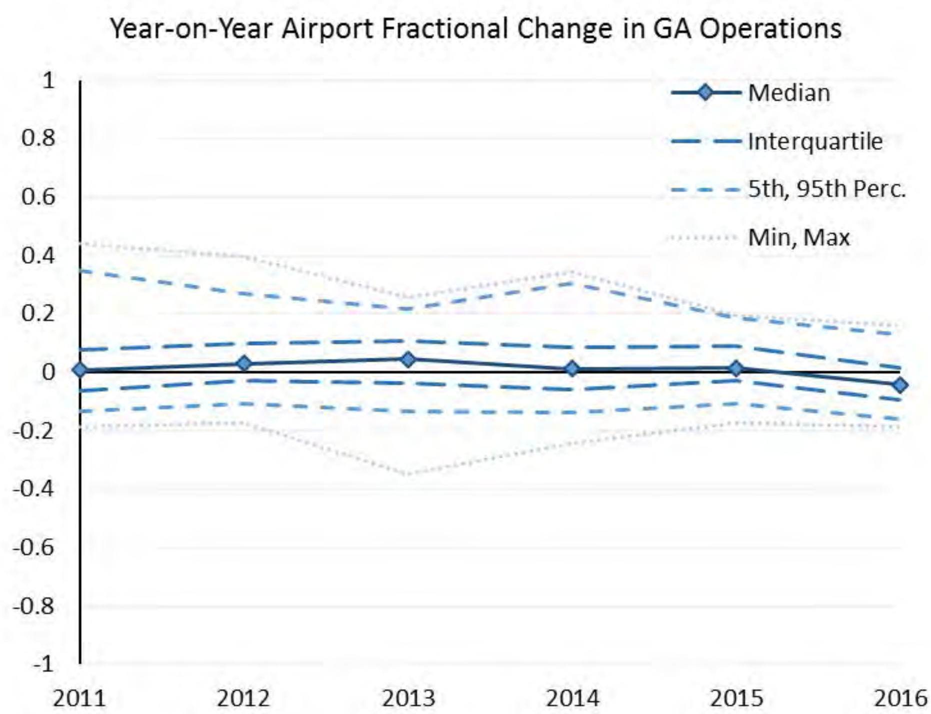

Figure B-1. Change in annual GA aircraft operations at the 50 most active airports by GA traffic from 2011 – 2016[8]

B.2 Diurnal profile

Section 2.2 of the main report details piston-engine aircraft emissions modeling at a GA airport facility (RHV). Part of this work addressed the fact that aircraft activity is not constant over the course of a day. Specifically, a detailed distribution of aircraft operations by hour was developed from on-site observations and survey data and applied in the modeling approach. Figure B-2 shows the distribution of operations across operational hours (i.e., diurnal profile) at RHV by aircraft class (SE vs. ME) and operational cycle-type (Full LTO vs. T&G). Distinct diurnal profiles were observed for weekdays (Figure B-2a) and weekends (Figure B-2b), with ME operations showing more variation between the two-day types.

[8] For this comparison, GA operations are the sum of itinerant general aviation and local civil aviation operations as reported in ATADS. Overflight and air taxi operations are not included.

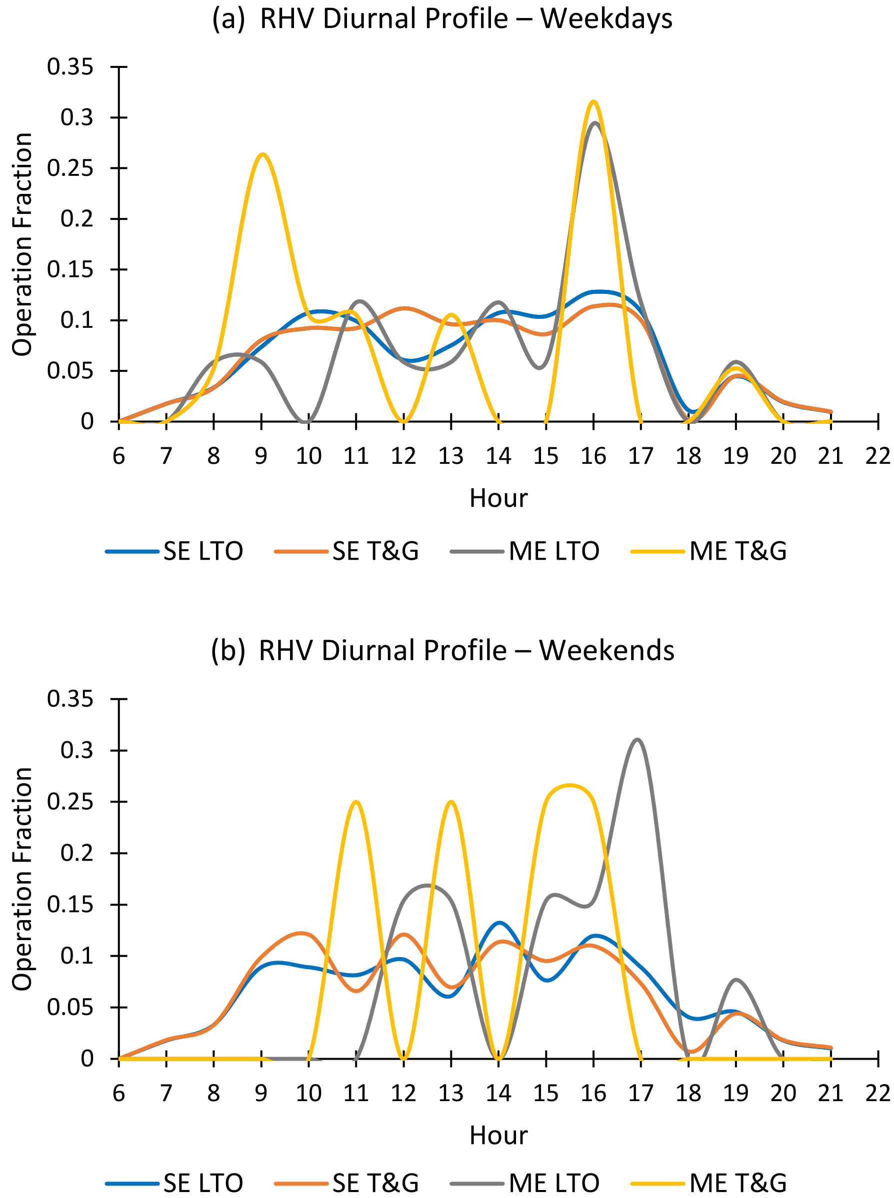

Figure B-2. Diurnal profile of aircraft operations by aircraft class, cycle-type, and day-type from RHV monitoring and survey data

Detailed hourly operational data similar to that presented in Figure B-2 is unavailable for each of the 13,153 airports in the national analysis. Yet, as described in Section 3 of the main report, applying the AQFs to characterize lead concentrations at airports nationwide requires detailed operational data as an input for each airport. For each hour, aircraft activity and wind direction data are used to assign operations to specific runways at each airport. As noted in Table 2 of Section 3, we used the diurnal operational profile shown in Figure B-2 to calculate hourly operations at each airport. We recognize that the distribution of operations can vary between facilities. Figure B-3 shows the hourly operational profiles at four airports. The profiles for RHV (weekday and weekend) represent the same operational profiles shown in Figure B-2, albeit not separated out by aircraft class and cycle-type. The profile for SMO was developed by on-site observation and survey data and underlies the lead modelling development study described in Section 2.1 (Carr et al. 2011). Two additional profiles developed from on-site observation and monitoring at the Richard Lloyd Jones airport (RVS) and Centennial airport (APA) are also shown as taken from the National Academies of Sciences Airport Cooperative Research Program Report *Quantifying Aircraft Lead Emissions at Airports*[9] (Heiken et al. 2014).

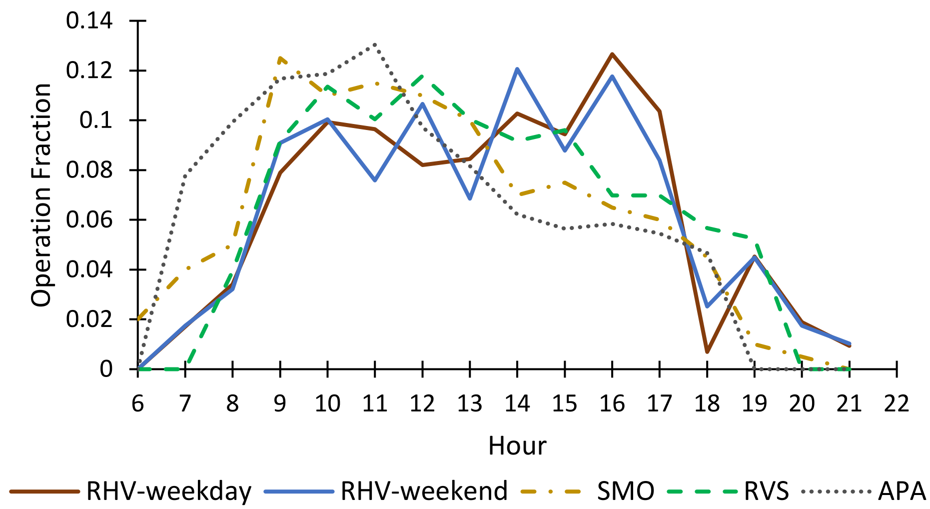

Figure B-3. Diurnal profiles of aircraft operations at four airports: RHV, SMO, RVS, and APA

A comparison of the diurnal profiles across these four facilities shows the same basic features: a ramp-up of activity in early morning, peaks in activity in late morning and early afternoon, and decreasing operations in the evening. For the National Analysis (Section 3 of main report), we selected the RHV profile as it provides the most detailed information in terms of how activity may vary over the course of a day based on aircraft class, operation types, as well as day type (weekday vs. weekend). In modeling studies, monthly average concentration has been shown to be insensitive to diurnal profile choice while holding daily operation count and runway assignment constant (Feinberg and Turner 2013). In characterizing concentrations using AQFs in the main report, the operational diurnal profile is an important parameter because runway assignment is based on predominant hourly wind direction as described in Section B.3 of this appendix.

[9] *Quantifying Aircraft Lead Emissions at Airports* also presents a diurnal operational profile for SMO; however, data was not available for all operational hours.

Because take-offs contribute more significantly to concentrations at the maximum impact location, a possible source of uncertainty is using the same diurnal profile for modeling landings and take-offs. To understand this sensitivity, the impact of using a generic "operational" diurnal profile vs. a "landing" or "take-off" was examined. For this choice of diurnal to be impactful on three-month averaged concentrations, two factors would need to occur: the difference between the diurnal profile of landings and the diurnal profile of take-off would need to be significantly different, and the average wind direction at the time of over-estimated take-offs would need to be significantly different than the average wind direction at the time of under-estimated take-offs.

Given that piston aircraft do not typically operate at night and that an aircraft must first take-off for it to land, there is an expectation that take-offs will (on average) occur earlier than landings. However, piston-engine aircraft typically perform short operational missions. Thus, while at the margins, landings should occur later than takeoffs, we do not expect the profile of landings and takeoffs to differ significantly. Airport surveys at six airport reported counts of landing and take-offs during operating hours or a subset of hours for between three and six days of operation. Operational survey data were excluded for any day that did not have survey data covering at least 80% of operational hours or for any days where both landing and take-off data were not available. Figure B-4 shows the difference in percentage points of the landing and take-off diurnal profiles at each of these airports as reported in survey data. The data confirms the expectation that, in the first (last) hour of operations monitored, take-offs were relatively more (less) prevalent than landings, but that profiles were otherwise similar over the day. The figure shows that, on average the difference between a landing diurnal profile and a takeoff diurnal profile is 2.6 percentage points. Further, 95% of examined hours show a difference of less than 6 percentage points between the landing diurnal profile and the take-off diurnal profile. Thus, using a generic "operation (LTO)" profile will, on average, over or under predict takeoffs by 1.3% in any given hour.

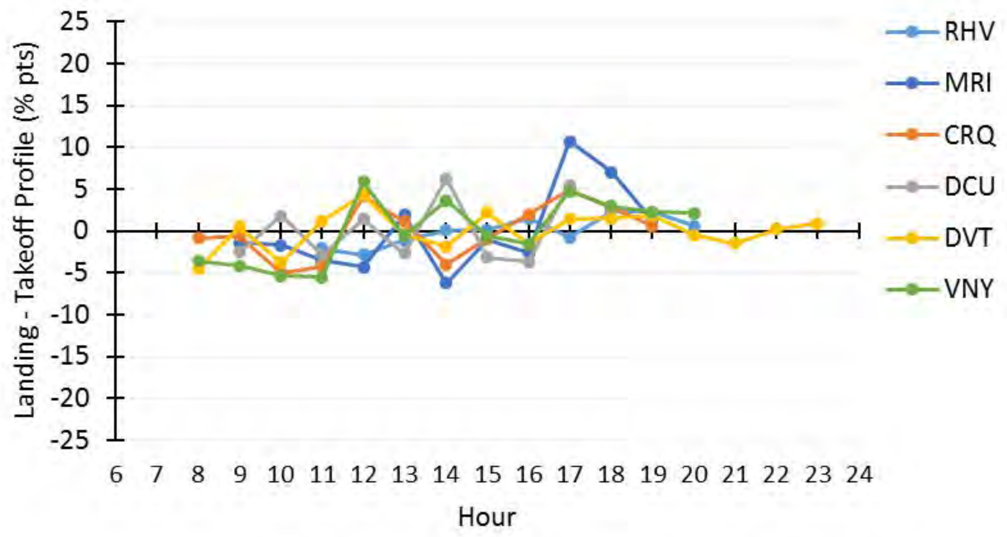

Figure B-4. Difference between landing diurnal profile and takeoff diurnal profile from 3 to 6 days of survey data at each of 6 airports

In the main report, a +/- 10% maximum 3-month concentration is considered in addressing airports where lead concentrations may approach or exceed 0.15 μg/m^3 (in addition to considering variation in other more sensitive parameters such as the expected split between multi- and single-engine aircraft), which far exceeds the +/- 1.3% uncertainty from differences in landing and take-off diurnal profile.

Further, while the average difference between a generic operation diurnal profile and a take-off only diurnal profile is 1.3%, the actual uncertainty in resulting 3-month average concentration may be even smaller. Since aircraft are assigned to runway primarily based on wind direction, a modeled difference in operations would require the wind direction to change significantly from the time in which takeoffs were overestimated to the time in which they are underestimated.

Figure B-5 shows the average wind speed at 938 ASOS stations nationwide for each hour of the day. Wind direction is normalized such that the wind direction at 00:00 is 0° at all stations. Each ASOS station is plotted along a circle of different unit radius, and each hour is modeled by a dot where angle represents difference in wind direction from 00:00 and color represents time of day. The figure shows that across all ASOS stations, 86% of all hours have average wind speeds that fall within 90° of the initial recorded wind direction. Therefore, for example, at a single runway airport, even if the diurnal profile were moving 2% of operations from the morning to the afternoon, there is an expectation that, averaged over a three-month period, those operations would still generally be assigned to the same runway end given consistent wind directions.

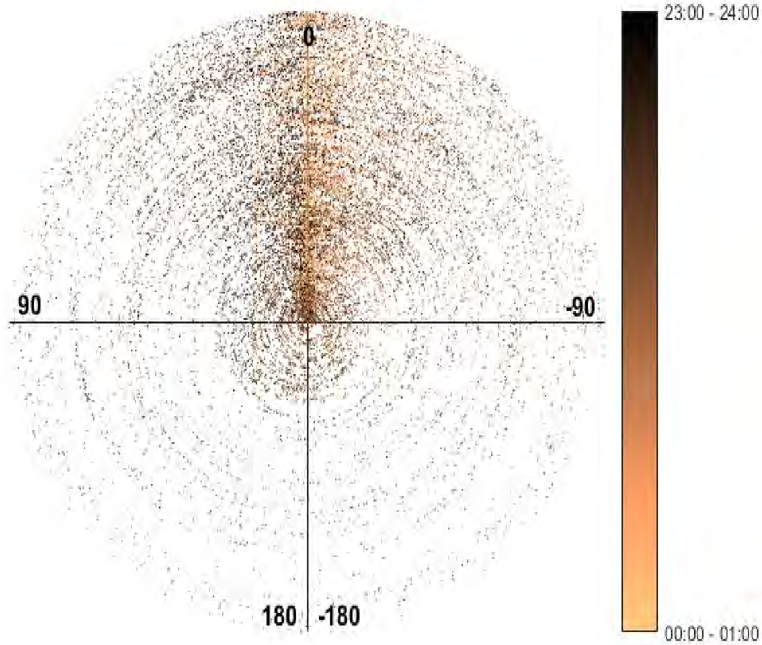

Figure B-5. Average wind direction by hour of the day at 938 ASOS stations

Given the evidence that 3-month average concentrations are insensitive to diurnal profile, the selection of the RHV diurnal profile is appropriate for the national analysis of lead concentrations.

B.3 Runway Assignment

The methodology for characterizing lead concentrations at airports nationwide presented in Section 3 of the main report requires every aircraft operation[10] at every airport be assigned to an active runway. Piston-engine aircraft typically take-off and land into the wind, and wind is the primary driver for selecting active runways (Lohr and Williams 2008). In the national and airport-specific analyses, hourly local wind direction data were used to identify on which runway piston-engine aircraft conduct take-off and landing operations. The active runway is determined using the minimum degree difference approach – identify the runway that has the smallest difference between the direction of the prevailing wind in that hour and the runway's heading in degrees and assign operations to that runway end. Where wind or runway headings are given with reference to magnetic north, directions are corrected to true north to maintain consistency across data sets.

In the national analysis presented in Section 3 of the main report, an active runway was selected for each airport for each hour of the day. The minimum degree difference approach

[10] One LTO cycle consists of two operations (takeoff and landing). Thus, the number of operations is divided in half to calculate LTOs per runway in the National Analysis.

was applied to 99.1% of airport-hour cases. In the remaining 0.9% of cases, there was no measurable wind, or wind direction data was missing. In these cases, operations were assigned assuming the most active runway configuration was consistent with the remaining hours of the day as there is an expectation that, absent other factors, an airport would maintain operational consistency.[11]

Of the 99.1% of airport-hour cases where airport-hour pair[12] data existed, there is only one runway that meets the minimum degree difference requirement for the overwhelming majority of cases (98.4%). However, in the remaining 1.6% of airport-hour pairs, the minimum degree difference approach was insufficient for assigning an active runway either because there were two or more runways with identical runway headings (parallel runways) or because the wind angle bisected two or more runway headings.

Section B.3.1 details the active runway configuration selection method for these scenarios, as well as the minimum degree difference scenario. Section B.3.2 describes the wind source data underlying the runway assignment methodology and discusses sources of uncertainty and caveats of the runway assignment method.

Section B.3.1 Runway Assignment Algorithm

This section describes the runway assignment algorithm. When hourly wind data is available and the predominant wind direction aligns with only one airport runway, the active runway end is assigned based on the minimum degree difference approach (Scenario 1). For cases where wind data is unavailable for a given hour or more than one runway aligns with the predominant wind direction, the choice of active runway end is dependent upon the layout of the airport runway system. These cases are described in Scenarios 2 through 5.

Scenario 1: Minimum Degree Difference Approach

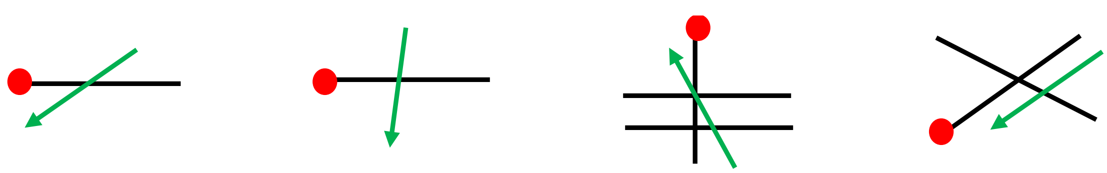

Figure B-6. Example Scenario 1 Configurations. Black lines represent runways, green arrows represent wind direction, and red dots represent the runway-end identified as active

Description: The minimum degree distance approach results in only one preferred available runway.

Occurrence: 98.4%

[11] In the few cases where wind direction data was missing for an entire day, operations were assigned to each runway end equally.

[12] An airport-hour pair is a matched pair of operation cycle (LTO/T&G) data and wind data for one airport over one specific hour of the year.

Selection Decision: All operations for the hour are assigned to the runway identified by the minimum degree distance approach.

Scenario 2: Non-Parallel Bisection

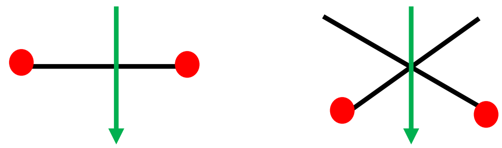

Figure B-7. Example Scenario 2 Configurations. Black lines represent runways, green arrows represent wind direction, and red dots represent the runway-end identified as active

Description: The prevailing wind bisects the heading of one or two non-parallel runways resulting in two options for an active runway, based on the minimum direction distance approach.
Occurrence: 0.15%
Selection Decision: All operations are assigned to the most active runway during the remaining hours of the day, based on the minimum direction distance approach. If more than one runways have been equally active during the remainder of the day, then operations for the hour are split evenly between the runway options.

Scenario 3: Parallel Runways

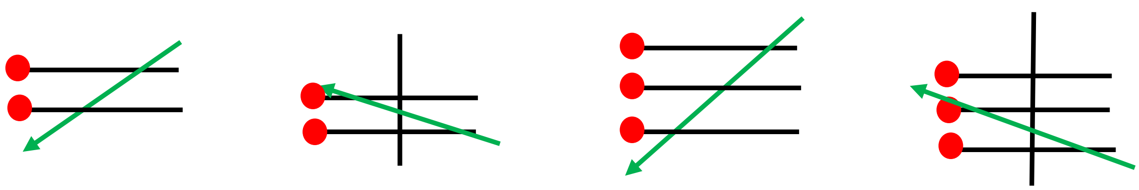

Figure B-8. Example Scenario 3 Configurations. Black lines represent runways, green arrows represent wind direction, and red dots represent the runway-end identified as active.

Description: The minimum direction distance approach identifies two or more parallel runways options for an active runway
Occurrence: 1.44%
Selection Decision: 90% of operations are assigned to a primary runway and 10% of operations are assigned to a second runway. Any 3rd or 4th parallel runway is assumed to not serve piston-engine aircraft. GA airports with multiple parallel runways will often have a preferential runway for operations, while airports serving GA and commercial operations may have a designated GA runway or a preferred take-off runway for all operations. Thus, the selection decision assumes a preferred operational runway. However,

operations can still occur on the non-preferred runway(s).[13] Thus, allocating 100% of operations to the preferred runway would over-estimate lead concentrations in the case where some operations occur on alternative runways.

Scenario 4: Combination Parallel and Bisection

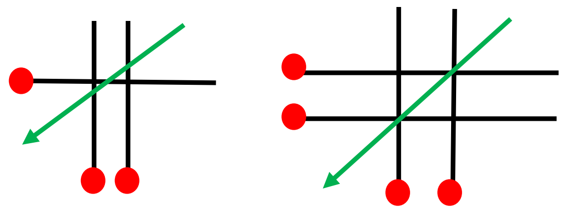

Figure B-9. Example Scenario 4 Configurations. Black lines represent runways, green arrows represent wind direction, and red dots represent the runway-end identified as active

Description: The minimum direction distance approach identifies both parallel and non-parallel runways

Occurrence: < 0.1%

Selection Decision: Parallel runways are first treated as runway groups. The approach for non-parallel bisection (Scenario 2) is applied between runway groups. The approach for parallel runways is then applied to the operations assigned to each runway group.

Scenario 5: Additional Multi-Runway Airports

Description: There are 15 airports in the national dataset with 5 or more runways. For these multi-runway airports, a subset of runways that serves piston-engine operations was identified from available operational, planning, or capacity information from the airport website or the FAA. These airports are described in more detail below.

Selection Decision: Only runways serving piston-engine operations are considered. Operation assignment rules then follow the selection criteria in Scenarios 1-4 noted above unless otherwise noted.

(a) Runways with only one identified piston-aircraft runway.

The following multi-runway airports have a single identified runway serving as the primary runway for piston-engine aircraft operations.

ATL: Based on the ATL Master Plan,[14] General Aviation hangars and other infrastructure are located on the north side of the airport. Therefore, piston-engine operations are assigned to runway 8L/26R following the approach laid out for Scenarios 1 and 2.

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[13] For example, at RHV, an airport with two parallel runways, most take-offs and landings occur on the eastern-most runway (31R/13L). However, the western-most runway is used frequently for touch-and-go operations.

[14] https://www.atl.com/wp-content/uploads/2016/12/ATL_ExecSumm_2015_101415_Spreads.pdf

DFW: Based on the DFW Master Plan, runway 17L/35R[15] is the preferred runway for General Aviation. Therefore, piston-engine operations are assigned to runway 17L/35R following approach laid out for Scenarios 1 and 2.

IAH: Based on the IAH Master Plan,[16] General Aviation exclusively uses runway 15R/33L. Therefore, piston-engine operations are assigned to runway 15R/33L following the approach laid out for Scenarios 1 and 2.

TCS: TCS has one asphalt runway (13/31) and four gravel runways. Therefore, piston-engine operations are assigned to runway 13/31 following the approach laid out for Scenarios 1 and 2.

TX99: TX99 is a private use airport with 5 turf runways. Piston-engine operations are assigned to runway 8R/26L following the approach laid out for Scenarios 1 and 2.

(b) Airports with two non-parallel identified piston-aircraft runways.

The following multi-runway airports have two identified non-parallel runways serving as the primary runways for piston-engine aircraft operations.

BOS: Based on the BOS Tower Standard Operating Procedures,[17] and information provided by Massport, the operator of the airport,[18] runway 14/32 is used exclusively for props and small jet aircraft while runway 4L/22R (purple) is not used for jets. Therefore, piston-engine operations are assigned to runways 14/32 and 4L/22R following the approach laid out for Scenarios 1 and 2.

DEN: Two runways were identified as serving General Aviation at DEN, runway 17R/35L is the preferred GA runway and runway 8/26 was selected as the preferred runway during a crosswind due to its proximity to the GA hangars. Therefore, piston-engine operations are assigned to runways 17R/35L and 8/26 following the approach laid out for Scenarios 1 and 2.

DTW: DTW has two non-parallel runways in close proximity to the general aviation area. Therefore, piston-engine operations are assigned to runways 3R/21L and 09/27L following the approach laid out for Scenarios 1 and 2.

FST: FST has two asphalt runways (12/30 and 3/21) and three turf runways in poor condition. Therefore, piston-engine operations are assigned to runways 12/30 and 3/21 following the approach laid out for Scenarios 1 and 2.

MDW: At MDW, General Aviation use runway 4L/22R during normal operations and runway 13R/31L during crosswinds as noted in the MDW Noise Compatibility Study.[19] Therefore, piston-engine operations are assigned to runways 4L/22R and 13R/31L following the approach laid out for Scenarios 1 and 2.

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[15] https://dfwairport.com/development/masterplan/index.php

[16] http://www.fly2houston.com/about-master-plans, 'Master Plan Volume 1'

[17] http://www.bvartcc.com/Portals/0/Air%20Traffic%20Control/ATC%20Documents/SOP/BVA_KBOS.pdf

[18] https://www.massport.com/environment/environmental-reporting/noise-abatement/runway-use/, https://www.massport.com/environment/environmental-reporting/noise-abatement/how-logan-operates/

[19] https://www.faa.gov/airports/planning_capacity/profiles/media/LGB-Airport-Capacity-Profile-Appendix-A-2014.pdf

MKE: Based on the MKE Master Plan Update Study,[20] piston aircraft primarily use runway 1L/19R and 7R/25L. Therefore, piston-engine operations are assigned to runways 1L/19R and 7R/25L following the approach laid out for Scenarios 1 and 2.

MWH: Based on the MWH Master Plan,[21] General Aviation is primarily assigned to runway 18/36 and runway14R/32L. Therefore, piston-engine operations are assigned to runways 18/36 and 14R/32L following the approach laid out for Scenarios 1 and 2.

(c) Other Runway Configurations

The following multi-runway airports have unique identified traffic patterns. Runways identified as serving piston-engine aircraft for these airports are shown in Figure B-10.

LGB: Based on the LGB Planning Capacity Profile from the FAA,[22] "smaller aircraft" use runways 25R/7L and 25L/7R. In addition, an Environmental Impact Report[23] showed that runways 16R/34L and 16L/34R are also used for general aviation. According to the EIR the parallel runways are used evenly (i.e., when 25R/7L and 25L/7R are used, 50% of activity is on the north runway and 50% is on the south runway. The same holds for runways 16R/34L and 16L/34R). Therefore, treating the parallel runways as runway groups, piston-engine operations are assigned to a runway group following the minimum degree difference approach. Within a runway group (i.e. for the identified parallel runway pair), operations are split evenly.

NRQ: NRQ has 4 sets of parallel runways (8 total runways). For each pair, one runway was selected as being eligible for piston-engine activity. Therefore, piston engine operations are assigned to the four non-parallel runways 04L/22R, 09L/27R, 13L/31R, and 18L/36R following the approach laid out for Scenarios 1 and 2.

ORD: Runway 9L/27R is used primarily for GA aircraft. In addition, runways 14R/32L and 4R/22L were identified as runways that could serve piston-engine aircraft when operations were prohibited on Runway 9L/27R during a crosswind. Therefore, piston-engine operations are assigned to the three non-parallel runways 9L/27R, 14R/32L, and 4R/22L following the approach laid out for Scenarios 1 and 2.

[20] https://www.mitchellairport.com/files/9213/0988/8039/MKEMasterPlanComplete.pdf
[21] http://moseslake.airportstudy.com/files/2012/12/MWH.Ch1_.DF_.6.23.14.pdf
[22] https://www.faa.gov/airports/planning_capacity/profiles/media/LGB-Airport-Capacity-Profile-Appendix-A-2014.pdf
[23] http://lbflying.com/files/ASNreport2009-05.pdf

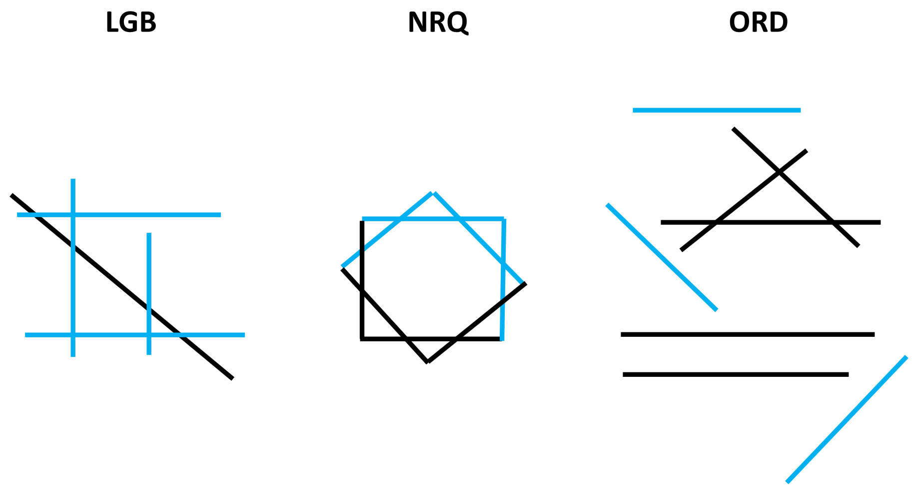
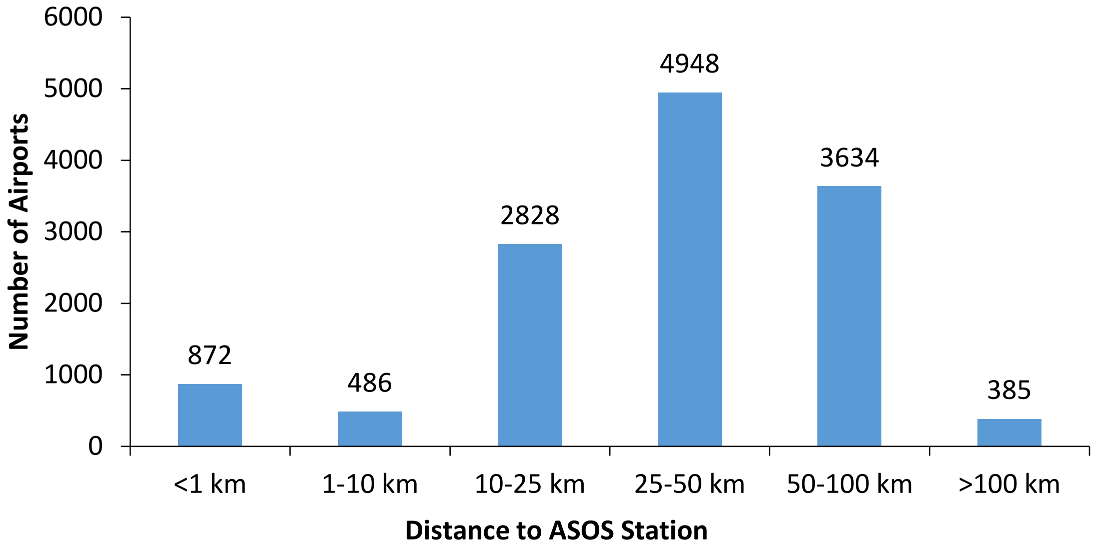


Figure B-10. Multi-runway airports with unique operational profiles. Black lines represent runways not serving piston-engine aircraft and blue lines represent runways serving piston-engine aircraft

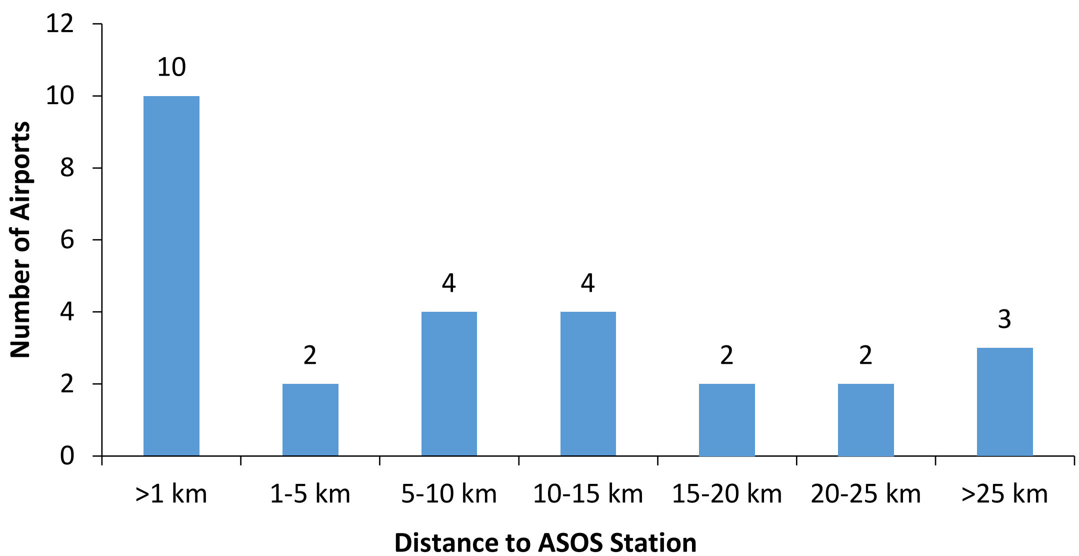
Section B.3.2 Wind Data Sources and Uncertainty

Wind direction data are available from Automated Surface Observing System (ASOS) meteorological stations. ASOS units are automated sensor suites that are designed to serve meteorological and aviation needs. These systems report visibility and meteorological data including wind speed and direction at approximately hourly intervals or when conditions change rapidly and cross aviation thresholds. Data is available in an online database through the National Centers for Environmental Information (NCEI).[24] At some airports, particularly those with higher levels of activity, an ASOS station is located on airport property, however, for other airports the nearest ASOS station may be several kilometers (km), or more, away. Of the 13,153 airports in the national analysis, 6.6% (872) have ASOS stations onsite (<1 km) (Figure B-11). Among the top 5% of airports by total piston-engine aircraft traffic, 48% have ASOS stations located within 1 km. In the airport-specific activity analysis presented in Section 3.3, 37% of airports (10) have an ASOS station onsite.

[24] ftp://ftp.ncdc.noaa.gov/pub/data/noaa/



(A)



(B)

Figure B-11. Distribution of the number of airports by distance to the closest ASOS station for airports in the national analysis (A), and airport-specific activity analysis (B). In both analyses, ASOS stations provided wind direction data that was used to identify the active runway end for piston-engine aircraft. Results from both analyses have greater uncertainty for airports with a longer distance to an ASOS station compared to airports closer to an ASOS station.

The relationship between ASOS distance and uncertainty in assignment of aircraft activity to a specific runway will depend on the distance to the nearest ASOS station, the number of available runways, and the geographic area in which the airport and ASOS station are located. For single runway airports, a relatively large shift in wind direction (an average shift of 90 degrees) is required for a shift in the active runway end for piston-engine aircraft, and thus such a shift would likely be detected at weather stations at even slightly longer distances (e.g., 10 km). At multi-runway airports where runway headings differ by fewer than 90°, small changes in predominant wind direction could change the active runway selection from hour to hour in the minimum-degree distance approach while the airport in practice is more likely to maintain a consistent operational pattern (Lohr 2008). Alternatively, prevailing wind direction may align with more than one runway in a given hour. In these case, the minimum-degree distance approach is likely to underestimate maximum lead concentrations as it predicts fewer operations at the dominant runway.

In areas with relatively consistent wind direction and minimal topographic perturbations (e.g., coastal regions), wind direction is likely to remain constant between an airport and an ASOS station even when the airport and ASOS stations are separated by some distance. As such, in these areas ASOS stations that are quite distant from an airport may provide accurate wind direction data for the purposes of identifying the active runway-end, which increases confidence in the approach used to estimate activity at the maximum impact area. In areas where geographic structure (e.g., mountainous regions, river valleys) creates uncertainty in the applicability of the wind direction data from an ASOS station to a different location, there is less confidence in the approach used to identify and quantify activity at the maximum impact area. At airports with less representative ASOS station wind data, model-extrapolated concentrations may be higher or lower than actual concentrations due to more or less piston-engine aircraft activity occurring at one runway end, versus others at the airport.

While wind direction is the primary driver for determining an airport's active runway, other factors may be important including operational restrictions, airport infrastructure location, runway length, and total airport capacity. For airports with significant operational restrictions or for multi-runway commercial airports that have designated GA or piston-aircraft runways, these operational considerations are an additional source of uncertainty.

B.4 Airport-Specific Observed Aircraft

As noted previously, operations conducted by piston-engine aircraft specifically are not reported. As described in Section 3.3 of the main report, the number and type of aircraft based at an airport (i.e., based aircraft data) were used to calculate airport-specific activity estimates for a subset of airports included in the national analysis. In the national analysis, national average fractions were used to partition activity estimates into piston-engine and non-piston-engine aircraft, and separately partition piston-engine aircraft activity in single- and multi-engine (SE and ME). For the airport-specific activity analysis, based aircraft data were selected as an alternative to the national average fractions for two reasons: 1) based aircraft data were available, unlike airport-specific counts of piston-engine LTOs, and 2) a comparison of observations of aircraft activity at six airports and based aircraft at those airports showed that based aircraft fractions are a reasonable proxy for activity fractions. The data used in that comparison are provided below.

Airport-specific information on piston-engine aircraft operations was collected for six airports from on-site observations and surveys. Further, four of these airports (CRQ, MRI, RHV, and VNY) had supplemental aircraft count data from noise-specific studies completed within the past ten years. For each of these six airports, data were collected on the type and operational characteristics of the observed General Aviation and Air Taxi fleet. Table B-2 shows the observed aircraft counts at each airport, as well as the comparison between the percentages of activity attributed to piston-engine aircraft, and then SE versus ME piston-engine aircraft, based on observational counts or the number of aircraft based at each airport.

Table B-2. Observed piston-engine aircraft from noise studies and onsite observational surveys

Airport	Number of Observ. Days	Number of Aircraft	Piston-engine		Single-Engine		Multi-Engine	
			Based Aircraft (%)	Observ. LTOs (%)	Based Aircraft (%)	Observ. LTOs (%)	Based Aircraft (%)	Observ. LTOs (%)
CRQ	14	2,163	63	66	90	93	10	7
MRI	5	827	98	95	95	94	5	6
PAO	7	1,268	98	95	90	99	10	1
RHV	7	2,209	99	88	92	97	8	3
SQL	7	1,018	96	86	90	98	10	2
VNY	30	15,809	59	52	77	95	23	5

Supplemental Sources:(URS 2005, Mead & Hunt 2007, LAWA 2008, LAWA 2011, HMMH 2013)

Table B-3 further summarizes the aircraft classes and operating modes at these six airports. Aircraft operational activity is broken out by jet and piston-engine aircraft, and piston-engine activity is further categorized into SE and ME aircraft activity. The share of piston-engine only activity by operational cycle-type (full LTO, T&G) is also shown.

Table B-3. Aircraft class and operation mode survey data

Airport	General Aviation and Air Taxi Activity						Piston Engine Aircraft and Activity Type			
	AT Jet (%)	AT ME (%)	GA and AT Jet (%)	GA and AT ME (%)	GA and AT SE (%)	GA and AT Heli (%)	ME LTO (%)	ME T&G (%)	SE LTO (%)	SE T&G (%)
CRQ	94.9	5.1	12.1*	4.4*	65.9*	17.6*	97.4	2.6	93.7	6.3
MRI			2.8	5.4	90.0	1.8	93.8	6.3	84.1	15.9
PAO			5.3	1.0	93.7	0.0	100.0	0.0	92.1	7.9
RHV			11.0	4.0	84.0	1.1	64.1	35.9	71.0	29.0
SQL			9.9	1.9	84.5	3.7	100.0	0.0	95.5	4.5
VNY			44.9	2.8	49.1	3.2	98.9	1.1	88.5	11.5

* These values are for GA aircraft only.

These studies showed that the fraction of SE and ME based aircraft (i.e., sum of SE and ME based aircraft over total based aircraft) was generally within 10% of observed piston-engine LTOs (Table B-2), and that use of based aircraft can reveal airport-specific fleet and operational characteristics (Tables B-2 and B-3). The general agreement between the number of based aircraft and observed activity data suggest that the fraction of SE and ME based aircraft could be used to estimate airport-specific piston-engine aircraft activity as a refinement of national average estimates. Of course, there are inherent uncertainties in based aircraft data, including the fact that some SE and ME based aircraft may be turboprop or other non-piston-engine aircraft; however, the comparisons with onsite activity counts suggest based aircraft provide reasonable, airport-specific data and FAA considers based aircraft data to be a reliable indicator of activity at small airports (FAA 2015).

B.5 Piston-Engine Rotorcraft

Piston-Engine Rotorcraft Activity at Heliports

Piston-engine rotorcraft operate at airports and heliports, and contribute a growing fraction of the activity conducted by rotorcraft (FAA 2011). Data on the activity of these aircraft is limited with activity data available from fewer than 100 of the 5,000 heliports having (FAA 2011). For the purposes of this report, fixed-wing aircraft are the focus of evaluation; however, methods similar to those applied here could be applied to estimate lead concentrations at and near heliports.

Piston-Engine Rotorcraft Activity at Airports

At airports, piston-engine aircraft include both fixed-wing airplanes and rotorcraft (i.e., helicopters). While fixed-wing aircraft take-off and land in consistent locations based on wind direction, rotorcraft may take-off from and land in multiple locations at an airport facility. As discussed in Section 1, the analysis in this report focuses on lead concentrations at and downwind of the maximum impact site attributable to fixed-wing piston-engine airplane activity at specified run-up locations adjacent to runway ends. Rotorcraft have not been included in this analysis.

If future analyses were to focus on calculating model-extrapolated concentrations for rotorcraft, then the scaling factors provided in Table B-4 below could be used with similar methods to those provided in Section 3 of the main report. For additional details on methods to develop the scaling factors or the underlying air quality modeling, see Sections 2.1 and 3.1 of the main report.

Table B-4. Rotorcraft air quality factor data

Operation Mode	Air Quality Factor ($\mu g/m^3$ per LTO)	Distance Description
Rotorcraft All Operational Modes	3.57×10^{-5}	Approximately 433 meters north of haypatch, alongside hangers near terminal
Rotorcraft Climb & Landing Only	6.07×10^{-7}	Approximately 18 meters southeast of haypatch

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Appendix C: Uncertainty Characterization

Section 4 of the report presents a quantitative and qualitative characterization of variability and uncertainty in lead concentration at and downwind of the maximum impact site at airports nationwide. This analysis focused on parameters identified in previous sections as particularly influential on the atmospheric concentration of lead from piston-aircraft operations. This appendix provides details on the data underlying this uncertainty analysis. Section C.1 describes the distribution of avgas lead concentrations used in the Monte Carlo analysis. Section C.2 describes the data underlying the evaluation of variation in run-up time on atmospheric lead concentration, as a function of downwind distance from the maximum impact site, which was also evaluated in the Monte Carlo analysis.

C.1 Avgas Lead Concentrations

As described in Section 4.3 of the report, the method for characterizing piston-engine aircraft attributable atmospheric lead concentration as a function of avgas lead concentration utilized a Monte Carlo analysis by treating avgas lead concentration as a bounded stochastic parameter based on ASTM standards for 100LL (1.70 – 2.12 g/gallon). Fuel samples may be spatially and temporally heterogeneous. EPA and FAA analyzed separate samples of avgas for lead. In total 118 samples were tested (2 samples were removed from further analysis due to likely data transcription errors). While these concentration data present the range of lead concentrations in individual samples, the range in average fuel lead concentration of total fuel consumed at an individual airport over a three-month period is likely more constrained. The average avgas lead concentration at a given airport over 3-months, the period over which the AQFs were developed, will likely represent an average of several fuel batches due to aircraft fueling at other airports and multiple fuel deliveries to the airport. By the central limit theorem, there is an expectation that the distribution of mean three-month fuel concentrations will approach a normal distribution. Thus, in the absence of spatial or temporal data on fuel lead concentration and given the sample size of n=116, a normal distribution was fit to the 116 fuel lead samples shown below in Figure C-1.

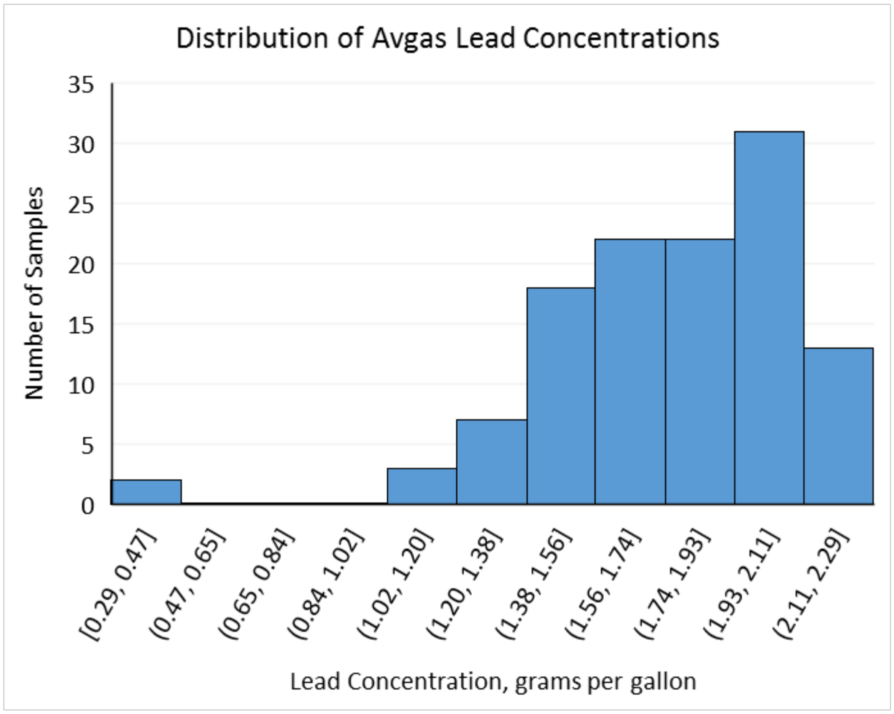

Figure C-1 Histogram of avgas lead concentrations from 116 samples.

The distribution had a mean of 1.79 g/gallon and a standard deviation of 0.27. For the Monte Carlo analysis, the distribution was bounded at a minimum of 1.70 g/gallon, the specification for 100 octane Very Low Lead (100VLL) avgas, and a maximum of 2.12 the maximum ASTM specification for 100LL. While samples of 100LL avgas were tested with concentrations above and below these bounds, the intent of the Monte Carlo analysis is to understand the potential ranges in average concentrations one would measure over a 3-month period as opposed to one sample from one location at one time.

More broadly in the report, the analysis focus is on piston-engine aircraft that operate using 100LL. The focus is driven largely by the predominate use of 100LL in the US piston-engine aircraft fleet. As reported by the FAA, approximately 190 million gallons of gasoline, both leaded aviation gasoline and unleaded automotive gasoline, were consumed by piston-engine aircraft in 2015 (FAA 2015)[1]. Of this, 92.5% was 100LL. As noted in the introduction, FAA survey data reports limited use of “100 Octane” aviation gasoline containing 4.24 grams of lead per gallon. The reported consumption of 100 Octane in 2015 was 8.9 million gallons, or 4.7% of the total volume of gasoline consumed by aircraft. In addition, FAA also reports use of unleaded automotive gasoline in aircraft (5.2 million gallons which comprised 2.8% of the total gasoline volume consumed). While it is expected that 100 Octane and automotive gasoline in aircraft are used at specific airports and other aircraft facilities, these two fuels were not modeled in this

[1] We report 2015 fuel consumption values here since it is the last year in which the FAA provided relative volumes for 100LL, 100 Octane, and automotive gasoline. Subsequent years do not present data for 100 Octane.

report given the relatively small volume of usage compared to 100LL (i.e., all operations are modeled as using 100LL).

C.2 Run-Up Time-in-Mode Distributions and Their Relationship to Atmospheric Lead Concentrations at and Downwind from the Maximum Impact Site

The AQFs presented in Section 3 of the report show the relationship between concentrations at the maximum impact site and at downwind locations given an operation cycle type (full LTO/T&G) and aircraft class (SE/ME). While the concentration gradients for each of the AQFs generally decrease monotonically with distance, two factors influence this relationship, namely: spacing of model receptors, and time-in-mode data. The AERMOD receptor grid spacing was 50 m for 1km up- and downwind of the airport along the axis of the runway. as shown in Appendix A. The AQFs are calculated using the nearest receptor location to the respective AQF distance. ME and SE operations have different default Times-In-Modes (TIM) based on data collected at the model airport. The TIM data will influence the timing and location of emissions. For instance, T&G operations have different spatial and temporal patterns than full LTOs, and do not include certain operational modes like run-up.

First, this section describes the distribution or run-up times observed at General Aviation airports. These observations inform the distribution of run-up times used in the Monte Carlo uncertainty analysis in the main report. Next, this section briefly describes the relationship between run-up time and atmospheric lead concentration at the model airport. Finally, this section describes the modeled relationship between run-up time and the maximum 3-month concentration at and downwind of the maximum impact site as applied in the Monte Carlo uncertainty analysis.

C.2.1 Run-Up Time-in-Mode Distributions

Time spent in run-up mode will vary from pilot to pilot as a function of personal preference, aircraft design, and training. Further, the distribution of run-up time-in-mode across all operations may vary from airport to airport dependent upon the fraction of pilots in training at that airport, airport run-up regulations, and local characteristics such as seasonal changes. Information on average run-up times was collected from studies that observed run-up operations (Carr et al. 2011, Heiken et al. 2014) and observations made at the model airport as described in this report (Section 2 of the main report and Appendix A). Six sets of run-up observations are represented across the three studies. One airport was surveyed separately by both Heiken et al. (2014) and Carr et al. (2011) while run-up distributions were separately surveyed for single-engine and multi-engine aircraft at the model airport in this report. The resulting 6 distributions (representing survey data from 4 unique airports) are shown in Figure C-2. More information on the surveying methods are available in Carr et al. 2011, Heiken et al. 2014, and Appendix A of this report. While the study designs, study durations, survey methods, and quality assurance approaches vary across the three studies, 40 to approximately 100 observations were collected across peak and off-peak hours and multiple days at each airport. For all airports where full data distributions were available, run-up duration observations showed consistent right-skewed distributions with median values between 49 and 73 seconds and means 5% to 30% higher than their respective medians.

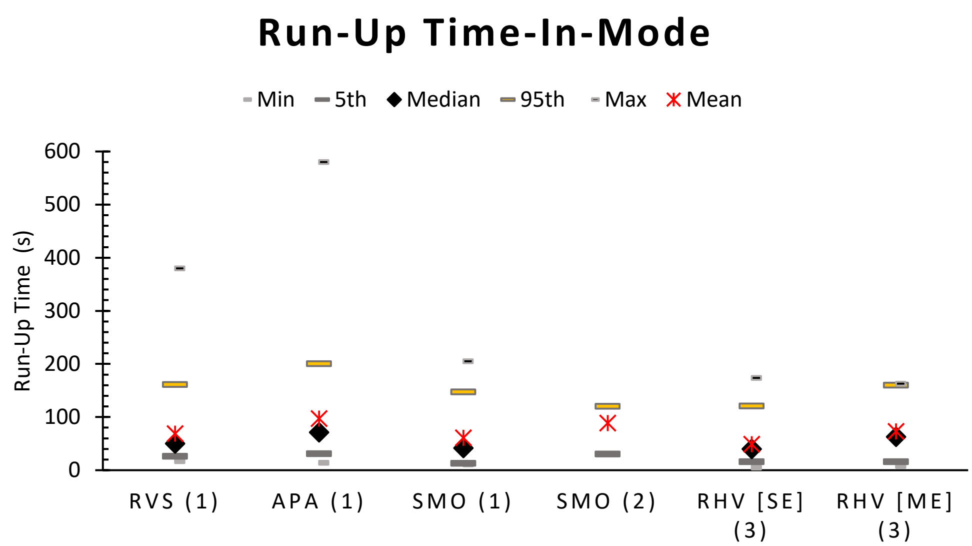

Figure C-2 Distribution of observed run-up duration observations across different studies. (1) Heiken et al. 2014, (2) Carr et al. 2011, (3) this report. The survey of run-up duration for this report separately characterized run-up for single-engine (SE) and multi-engine (ME) aircraft.

C.2.2 Relationship Between Run-Up Time and Atmospheric Lead Concentration

As discussed in the main report, previous analyses have identified that atmospheric lead concentrations are sensitive to run-up operation characteristics (Carr et al. 2011, Feinberg and Turner 2013, Heiken et al. 2014). For example, Feinberg and Turner (2013) found run-up emissions to be the single largest contributor to ground-level lead concentrations, while only accounting for about 11% of airport lead emissions. Their modeling found that changing the emissions attributable to run-up from 3% of modeled emissions to 5% of modeled emissions resulted in a 34% increase in annual atmospheric lead concentrations.

A sensitivity analysis was conducted at the model airport as described in Section 2 of the main report. The sensitivity analysis examined the influence of run-up duration on 3-month average lead concentrations at and downwind of the maximum impact site for one 3-month period (January-March). The analysis was run for three run-up durations for each aircraft class: 16, 40, and 121 seconds for SE aircraft and 16, 63, and 160 seconds for ME aircraft, which correspond to the 5th percentile, median, and 95th percentiles of SE and ME run-up times observed at the model airport, respectively. The concentration from only run-up emissions at the maximum impact site receptor was 0.034 μg/m^3 for the 5th percentile, 0.257 μg/m^3 for the 95th percentile, and 0.092 μg/m^3 for the default run-up duration. Lead concentrations attributable to run-up emissions alone exceeded the urban background lead concentration at a downwind distance of up to 275 m using the 95th percentile run-up duration and 75 m using the 5th percentile run-up duration. January-March 3-month average lead concentrations from run-up emissions alone are shown in Figures C-3 (5^{th} percentile run-up duration) C-4 (default run-up duration) and C-5 (95^{th} percentile run-up duration).

Figure C-3 January-March 3-month average lead air concentrations (µg/m^3) at the model airport from run-up mode alone using the 5^{th} percentile run-up duration.

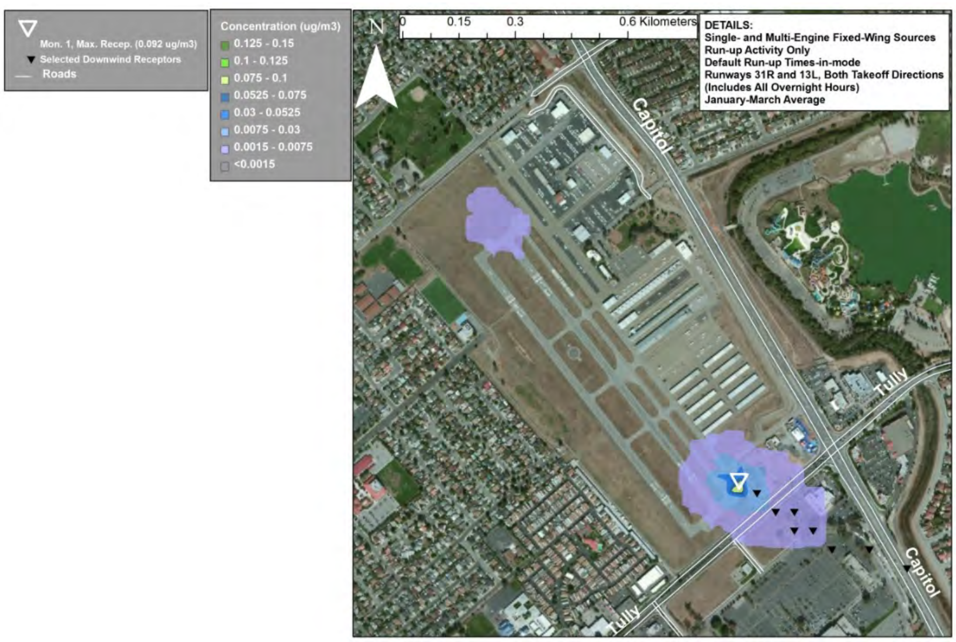

Figure C-4 January-March 3-month average lead air concentrations (µg/m^3) at the model airport from run-up mode alone using the default run-up duration.

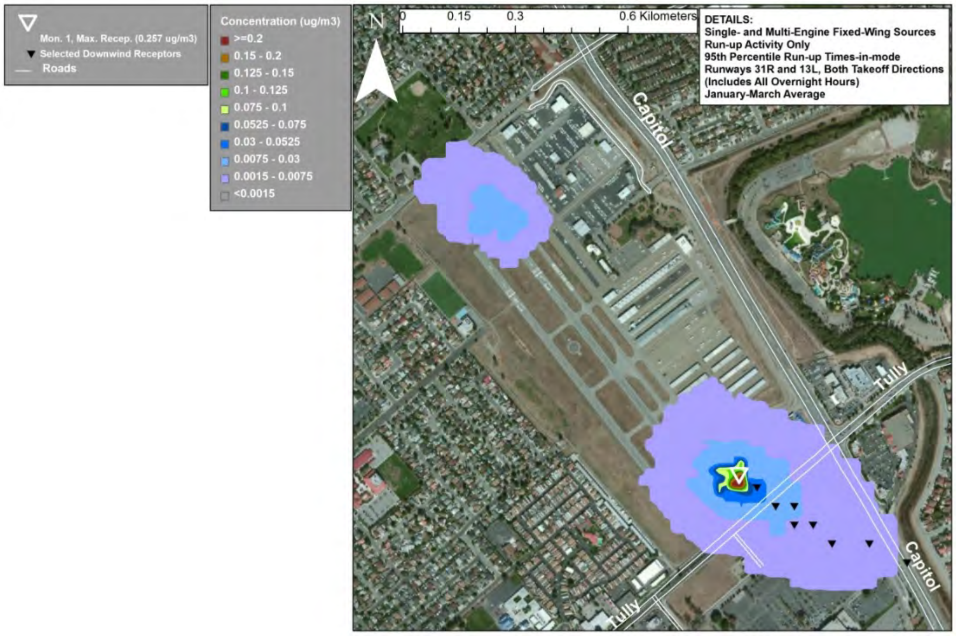

Figure C-5 January-March 3-month average lead air concentrations (μg/m^3) at the model airport from run-up mode alone using the 95th percentile run-up duration.

C.2.3 Characterization of the relationship between run-up time-in-mode and atmospheric concentration as a function of distance from the maximum impact site

In order to quantitatively evaluate the variability in lead concentrations with run-up time for SE and ME aircraft at each receptor site (described in Section 4 of the report), individual relationships were developed as described here. The impact of run up-time on lead concentration was characterized at the model airport by modeling atmospheric lead concentrations from piston-engine aircraft and varying the run-up time while holding all other parameters constant.[2] SE and ME aircraft were modeled separately as SE and ME aircraft have differing emission rates and different time-in-mode distributions for run-up, as shown in Figure C-1. The analysis was run using the 5th percentile, median, and 95th percentile run-up TIMs observed at the model airport. The resulting maximum 3-month average lead concentrations are shown in Figure C-6. The rows of Figure C-6 correspond to SE and ME aircraft results respectively, and the columns present results at the maximum impact site and 400m downwind from the maximum impact site respectively.

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[2] The characterization of lead concentrations at the model airport and the associated parameter assumptions are highlighted in Section 2 of the report.

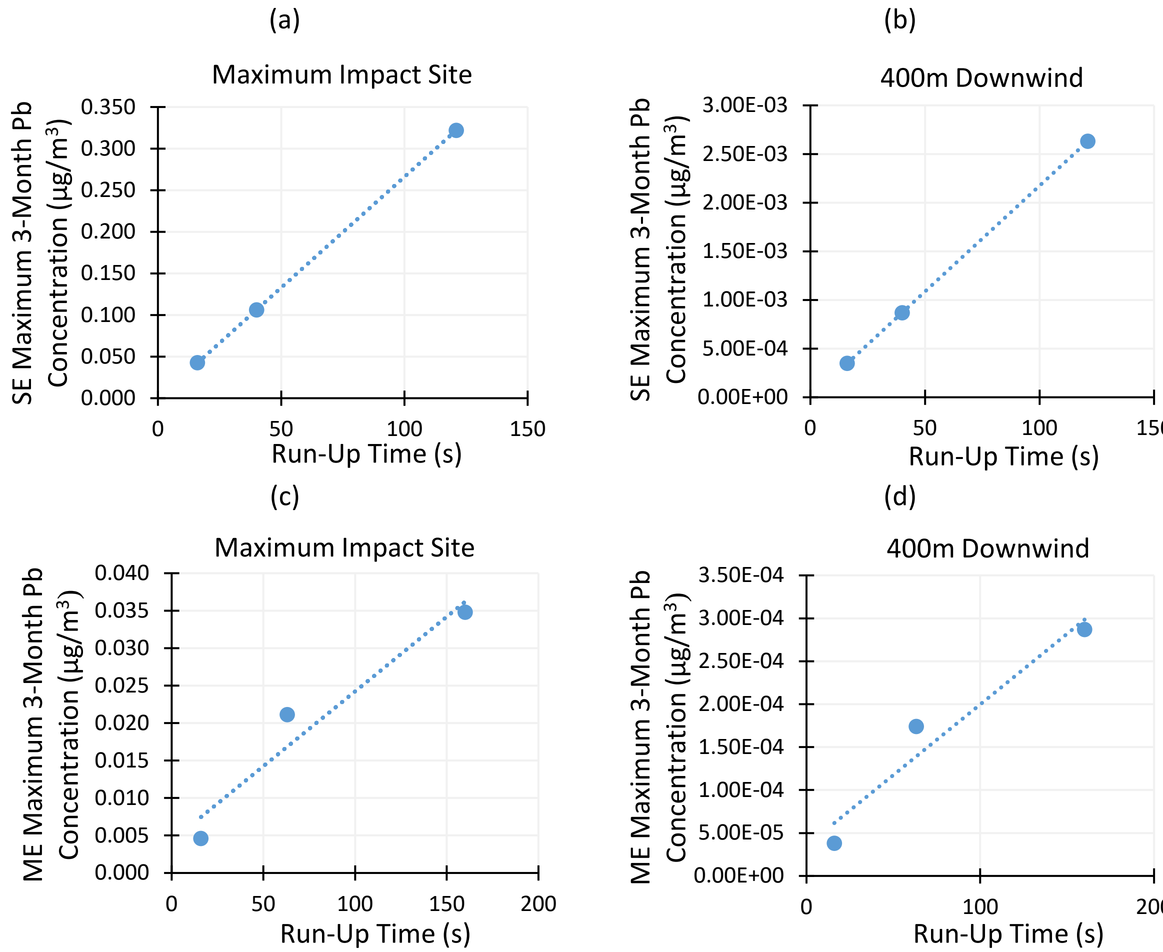

Figure C-6 Relationship between run-up duration and lead concentration at the model airport

The relationship between run-up time and resulting concentration is linear at both the maximum impact site and at each downwind location.[3] Unique linear equations were derived for each concentration site for both SE and ME operations, where the slope represents the sensitivity of the total concentration to run-up duration. Consistent with a decreasing concentration gradient downwind of the maximum concentration site, the slopes of the linear relationships between run-up time and concentration decrease from one site to a site further downwind. The equations for the maximum impact site and each of the downwind locations are given in Table C-1 where the independent variable *x* is run-up time and the dependent variable *y* is the resulting maximum 3-month average concentration.

[3] Some of the SE sites demonstrated a linear relationship between run-up time and resulting concentration with a negative intercept. Further, some of the ME sites, while approximately linear between 16 and 163 seconds, suggest a relationship that may also be characterized as logarithmic. These results indicate that, while characterizing the relationship between run-up and resulting concentration as linear may be appropriate for the modeled run-up times, further work is necessary to extrapolate these results far beyond these modeled run-up times.

Table C-1 Relationship between run-up time-in-mode and maximum 3-month average lead concentration as a function of distance from the maximum impact site.

Site	Single-Engine Relationship	Multi-Engine Relationship
Maximum Impact Site	$y = (2.66x - 0.0290) \times 10^{-3}$	$y = (1.99x + 42.8) \times 10^{-4}$
50m Downwind	$y = (4.30x + 0.0081) \times 10^{-4}$	$y = (3.21x + 68.6) \times 10^{-5}$
100m Downwind	$y = (1.42x + 0.0115) \times 10^{-4}$	$y = (1.05x + 22.5) \times 10^{-5}$
150m Downwind	$y = (9.09x - 0.0672) \times 10^{-5}$	$y = (6.87x + 148) \times 10^{-6}$
200m Downwind	$y = (6.78x + 0.0120) \times 10^{-5}$	$y = (4.94x + 105) \times 10^{-6}$
250m Downwind	$y = (5.19x + 0.0250) \times 10^{-5}$	$y = (3.89x + 82.8) \times 10^{-6}$
300m Downwind	$y = (3.31x - 0.0039) \times 10^{-5}$	$y = (2.46x + 51.9) \times 10^{-6}$
400m Downwind	$y = (2.18x - 0.0132) \times 10^{-5}$	$y = (1.65x + 35.2) \times 10^{-6}$
500m Downwind	$y = (1.41x + 0.0016) \times 10^{-5}$	$y = (1.07x + 23.0) \times 10^{-6}$

The relationship between run-up time [*x*] and resulting concentration [*y*] is linear for a relevant range of run-up times, and for a known run-up time [x_{Initial}], the concentration at each downwind location is characterized at each airport [$y(x_{\text{Initial}})$] as presented in Section 4 of the report. Thus, the percentage change in lead concentration from a change in run-up time can be calculated as:

$$\%Diff = \frac{(y(x) - y(x_{median}))}{y(x_{median})} \qquad \text{(Equation C-1)}$$

Equation C-1 can be used to vary resulting concentrations as a function of the aircraft run-up time-in-mode and allows for the characterization of atmospheric concentrations while varying additional parameters such as fuel lead concentration. Therefore, Equation C-1 is used to understand the uncertainty and potential variability of lead concentrations in the Monte Carlo analysis presented in Section 4 of the report.

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