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ACRP REPORT 7

Aircraft and Airport-Related Hazardous Air Pollutants: Research Needs and Analysis

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AIRPORT COOPERATIVE RESEARCH PROGRAM

Airports are vital national resources. They serve a key role in transportation of people and goods and in regional, national, and international commerce. They are where the nation's aviation system connects with other modes of transportation and where federal responsibility for managing and regulating air traffic operations intersects with the role of state and local governments that own and operate most airports. Research is necessary to solve common operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the airport industry. The Airport Cooperative Research Program (ACRP) serves as one of the principal means by which the airport industry can develop innovative near-term solutions to meet demands placed on it.

The need for ACRP was identified in *TRB Special Report 272: Airport Research Needs: Cooperative Solutions* in 2003, based on a study sponsored by the Federal Aviation Administration (FAA). The ACRP carries out applied research on problems that are shared by airport operating agencies and are not being adequately addressed by existing federal research programs. It is modeled after the successful National Cooperative Highway Research Program and Transit Cooperative Research Program. The ACRP undertakes research and other technical activities in a variety of airport subject areas, including design, construction, maintenance, operations, safety, security, policy, planning, human resources, and administration. The ACRP provides a forum where airport operators can cooperatively address common operational problems.

The ACRP was authorized in December 2003 as part of the Vision 100-Century of Aviation Reauthorization Act. The primary participants in the ACRP are (1) an independent governing board, the ACRP Oversight Committee (AOC), appointed by the Secretary of the U.S. Department of Transportation with representation from airport operating agencies, other stakeholders, and relevant industry organizations such as the Airports Council International-North America (ACI-NA), the American Association of Airport Executives (AAAE), the National Association of State Aviation Officials (NASAO), and the Air Transport Association (ATA) as vital links to the airport community; (2) the TRB as program manager and secretariat for the governing board; and (3) the FAA as program sponsor. In October 2005, the FAA executed a contract with the National Academies formally initiating the program.

The ACRP benefits from the cooperation and participation of airport professionals, air carriers, shippers, state and local government officials, equipment and service suppliers, other airport users, and research organizations. Each of these participants has different interests and responsibilities, and each is an integral part of this cooperative research effort.

Research problem statements for the ACRP are solicited periodically but may be submitted to the TRB by anyone at any time. It is the responsibility of the AOC to formulate the research program by identifying the highest priority projects and defining funding levels and expected products.

Once selected, each ACRP project is assigned to an expert panel, appointed by the TRB. Panels include experienced practitioners and research specialists; heavy emphasis is placed on including airport professionals, the intended users of the research products. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, ACRP project panels serve voluntarily without compensation.

Primary emphasis is placed on disseminating ACRP results to the intended end-users of the research: airport operating agencies, service providers, and suppliers. The ACRP produces a series of research reports for use by airport operators, local agencies, the FAA, and other interested parties, and industry associations may arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by airport-industry practitioners.

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COOPERATIVE RESEARCH PROGRAMS

FOREWORD

By Christine L. Gerencher
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ACRP Report 7: Aircraft and Airport-Related Hazardous Air Pollutants: Research Needs and Analysis provides guidance on the most important projects to the airport community for ACRP consideration in the area of hazardous air pollutants (HAPs). This report examines the state of the latest research on aviation-related HAP emissions and identifies knowledge gaps that existing research has not yet bridged. These gaps and related research needs are then prioritized based on the ability of research in those areas to provide airports a better understanding of the relationship of the type and amount of HAPs being emitted and their impacts. While the main purpose of this report is to identify key research areas important to the airport community for ACRP consideration, research communities at large will also benefit from this report's comprehensive analysis of aviation-related HAP research needs.

Increasingly, airports and the Federal Aviation Administration (FAA) are asked by various agencies and communities surrounding airports to analyze the health impacts of aircraft and other airport-related sources of air toxics, also known as hazardous air pollutants (HAPs), in National Environmental Policy Act (NEPA) and state-level documents. However, unlike criteria air pollutants, information on the emission, transformation, and transport of aviation-related HAPs and their health impacts is extremely rudimentary. Without a better understanding of aviation HAP emissions, airports are unable to develop accurate inventories and are left with little guidance on how to provide their state and local constituencies with the information they are increasingly demanding.

It became evident during the development of this report that there is a great deal of research that needs to be done in this area, particularly to get more robust health impact data on HAPs and to quantifying the emissions from the various sources in the airport environment. The prioritization of research needs in this report, therefore, was based on the contributions the airport community could provide to the field of aviation-related HAPs analysis while giving the airport community critical pieces of information to assist them in conducting more thorough and accurate HAP emissions inventories.

ACRP Report 7 concludes with identification of four suggested research projects for ACRP consideration, including detailed problem statements for submittal through the ACRP solicitation process. The research projects outlined in these statements provide a blueprint to bridge those critical research gaps identified in the report, which will benefit airports by improving the accuracy of information used in HAP emissions inventories.

C O N T E N T S

S U M M A R Y

Aircraft and Airport-Related Hazardous Air Pollutants: Research Needs and Analysis

Information has been collected regarding airport-related hazardous air pollutants (HAPs) via a literature review and communication with experts in the field. The state of knowledge has been assessed, information gaps have been identified, and research topics to address these gaps have been proposed.

A prioritized list of gas-phase HAPs emitted by airport emission sources has been constructed based on the product of the compounds' toxicities and emission rates. This list consists of acrolein (propenal), formaldehyde, 1,3-butadiene, naphthalene, benzene, acetaldehyde, ethylbenzene, and propanal (propionaldehyde). Glyoxal, methylglyoxal, and crotonaldehyde (butenal), although not officially hazardous air pollutants, may be comparable in importance to the compounds listed above.

Within the airport perimeter, aircraft engines during idle/taxi are the largest emission source for most of these compounds, although gasoline engines (used in ground access vehicles and some ground service equipment) can in some cases emit comparable amounts of benzene and 1,3-butadiene. The sources that contribute the most to human *exposure* depend heavily on the particular exposure group and airport and cannot be easily generalized. For example, nearby residents' exposure may be most affected by the aircraft or ground access vehicles depending on meteorology and the relative location of busy roadways, airport runways, and residential areas.

Future studies such as health risk assessments, however, should not limit themselves to the above compounds and should consider all types of particulate matter (refer to *ACRP Report 6: Research Needs Associated with Particulate Emissions at Airports*) and site-specific parameters such as the relative location of emission sources and the relevant exposure groups.

It is recommended that ACRP fund the following research topics. Research on these topics would enable airport operators to develop more accurate HAP emission inventories and/or to reduce emissions most cost effectively.

1. **Quantify the dependence of HAP emissions from aircraft as a function of ambient conditions (temperature, pressure, humidity) and engine technology.** Gas-phase HAP emissions increase greatly with decreasing temperatures; however, they have never been measured at sub-freezing temperatures. This can result in over a factor of two uncertainty in emission inventories.
2. **Quantify the actual thrust levels used by aircraft during the idle/taxi phase of a landing and/or take-off cycle.** The current uncertainty in the actual thrust levels used during taxi/idle results in up to a factor of two uncertainty in HAP emission inventories.
3. **Quantify HAP emissions from general aviation aircraft.** With the exception of lead, aircraft emissions from piston engine aircraft, which are unregulated, remain unquantified.

4. **Identify the emission sources most important to on-airport and off-airport exposure.** Exposure (and therefore human health risk) depends on several factors such as meteorology and the relative location of emission sources and exposure groups. Such a project will help airport operators to identify the "low-hanging fruit" with regards to minimizing the health risk presented by the various emission sources present at an airport.

In addition to the information gaps identified in the research statements above, there are information gaps related to the current state of knowledge regarding the toxicity of the following two classes of compounds: alkenes and certain aldehydes (including glyoxal, methylglyoxal, and crotonaldehyde). Of these compounds, addressing information gaps for glyoxal, methylglyoxal, and crotonaldehyde is most critical, as they may be emitted in sizeable quantities, and limited toxicological information for these compounds indicates their toxicity could be comparable to that of formaldehyde, acetaldehyde, and acrolein. The toxicity of glyoxal, methylglyoxal, and crotonaldehyde is highly uncertain.

SECTION 1

Introduction

1.1 Report Motivation

Understanding the emission sources, ambient concentrations, human exposure parameters, and health risk factors of hazardous air pollutants associated with an airport is necessary to fully protect the health of personnel working at the airport, minimize exposure for the traveling public, and avoid adverse impacts on the air quality of nearby neighborhoods. The goal of this project is to produce a prioritized agenda for future research that will address critical information gaps associated with airport-related hazardous air pollutants (HAPs).

1.2 Report Overview

A literature review was conducted on the following topics:

- Aircraft/airport HAP emission factors,
- Airport activity and fuel use factors,
- Related ambient HAP concentrations,
- Dispersion modeling of airport emissions, and
- Toxicology of aviation-related HAPs.

This information was used to

- Assess the current state of knowledge regarding airport-related HAPs,
- Identify the information gaps that limit our ability to assess fully the impact of airport HAP emissions on human health,
- Determine which compounds are likely to present the most risk to human health, and
- Determine which aviation-related emission sources are most significant.

The literature survey drew on several sources including: (1) Boolean searches using Google Scholar and *Web of Science*, and (2) communication (telephone/email) with aviation researchers and airport operators. These searches yielded information in several forms including articles published in the peer-reviewed literature, available emission inventories, reports from recent aircraft emission measurement campaigns, airport environmental impact statements, and unpublished data (recent experimental results that are not yet published and emissions data collected by airport operators). Our findings are used to create a prioritized research agenda that will address the identified information gaps.

1.3 Background Information on Hazardous Air Pollutants

The U.S. Environmental Protection Agency (EPA) has six designated "criteria" air pollutants, which are known to be damaging to public health: ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), lead (Pb), and particulate matter (PM). There is a national network of monitoring stations that make continuous measurements of these pollutants. The concentrations of these pollutants must not exceed pre-set National Ambient Air Quality Standards (NAAQS) established by EPA to protect public health and welfare.

In addition to the criteria pollutants, there are more than one hundred other air pollutants that are either known or suspected to be hazardous. These are known as "hazardous air pollutants" or HAPs, or alternately "air toxics." Two commonly known examples are benzene and formaldehyde. As dictated by the Clean Air Act, the EPA maintains a list of these HAPs. Additionally, for mobile source emissions the EPA maintains a "Master List of Compounds Emitted by Mobile Sources," which is available at www.epa.gov/otaq/toxics.htm. Aside from federal standards, many individual states also have programs governing emissions of HAPs. In many instances, the list of state HAPs differs with the USEPA designation. The nature and structure of these programs differ considerably from state to state. Measurements of ambient HAP concentrations are not as widespread as those of the

criteria pollutants. Descriptions of individual HAPs and their affects on human health have been published in recent documents (URS 2003; FAA 2005). There are many sources that emit HAPs—ground transportation, construction, power generation, dry cleaning, and aviation—to name a few. At airports there are several sources of HAP emissions. A partial list of "airside" sources (vehicles that do not leave the airport) includes baggage tugs and other ground support equipment (GSE), solvent use, and the aircraft themselves. There are additional "roadside" sources, also called ground access vehicles (GAVs), that consist mainly of on-road vehicles (cars, buses, shuttles, etc.).

This report focuses on gas-phase HAPs, which in the airport context is mainly a subcategory of volatile organic compounds (VOCs). A related report, *ACRP Report 6: Research Needs Associated with Particulate Emissions at Airports,* addresses airport particulate matter emissions.

1.4 Approach Used for Identifying Information Gaps Associated with Airport-Related Hazardous Air Pollutants

What is the risk presented by airport-related hazardous air pollutants? Information gaps preclude a definitive answer to this question; however, knowledge of which airport sources matter the most and which hazardous air pollutants are most important will surely assist in addressing that question. This section discusses the approach used to determine which pieces of information are most crucial to determining the relative risk presented by airport-related HAPs. Note that this report is not a human health risk assessment and therefore does not evaluate knowledge gaps based on exposure risk, which is explained in more detail further in this section.

In this report airport emission sources are divided into four main categories:

1. Aircraft,
2. GSE (baggage tugs, belt loaders, etc.) and auxiliary power units (APU),
3. GAV (cars, buses, shuttles, etc.), and
4. Stationary sources (power generation, HVAC systems, solvent use, etc.)

Quantification of the "risk" posed to a particular exposure group by the emissions of HAPs by these numerous emission sources at an airport is complicated. The risk presented to human health by any particular compound is a function of *exposure* and *toxicity*. Exposure and toxicity are in turn both a function of the exposure pathway (e.g., ingestion, dermal contact, inhalation). For the inhalation pathway, exposure is a function of exposure time, and the concentration of a pollutant, which is determined by the quantity *emitted* from the various sources and how these emissions disperse and react in the air, as depicted in Figure 1.

The emission sources and pollutants that present the greatest risk to the health of a baggage tug operator may differ greatly from those that affect the health of a nearby resident. Consider a few exposure groups related to an airport (Figure 2).

A baggage tug operator's exposure to airport pollutants is presumably greatly influenced by those emission sources that she or he is closest to, for example, baggage tugs, belt loaders, and possibly idling aircraft engines and auxiliary power units. Residential Neighborhood 3 is sandwiched between the airport runways and the ocean. Since there are few busy roads nearby, the emission source to which these residents experience the most exposure might be the aircraft themselves during the various phases of the landing take-off (LTO) cycle. Residential Neighborhood 1 is near the airport ground traffic, the downtown business district, and a number of busy roads. Residents of Neighborhood 1 are presumably exposed to a wider range of emission sources—airport and non-airport related. Furthermore, the local meteorology (e.g., wind direction and speed) is another parameter that greatly affects the relative importance of these various airport emission sources.

As evident by the example of just this one airport and a few exposure groups, there are many parameters that determine risk. A full health risk assessment that is relevant for the closest exposure groups must be based on exposure and toxicity, which must be done on a case-by-case basis and may be different from airport to airport. This is beyond the scope of this report. An example of such an undertaking is the 2003 supplemental environmental impact report for Oakland International Airport (OAK) (CDM 2003), which explicitly calculated the risk presented to a number of exposure groups due to emissions from OAK.

This report provides a preliminary assessment of which airport sources and which individual hazardous air pollutants should be closely considered in future research. This assessment is based on both the toxicity of the individual pollutants and the amount emitted. It is not possible to identify human health risk generically, as such effects require an extensive amount of information regarding exposure that is uniquely site-specific. Thus, the approach deployed in this evaluation resulted in the identification of airport-related sources, their associated HAPs, and the relative toxicity of the individual HAPs. With this approach, key HAPs and associated sources were identified. The rationale for using this approach is that HAPs inventories can be quantified much more easily than exposure, and thus the results of the analysis presented herein can be considered relevant to most commercial airports. The
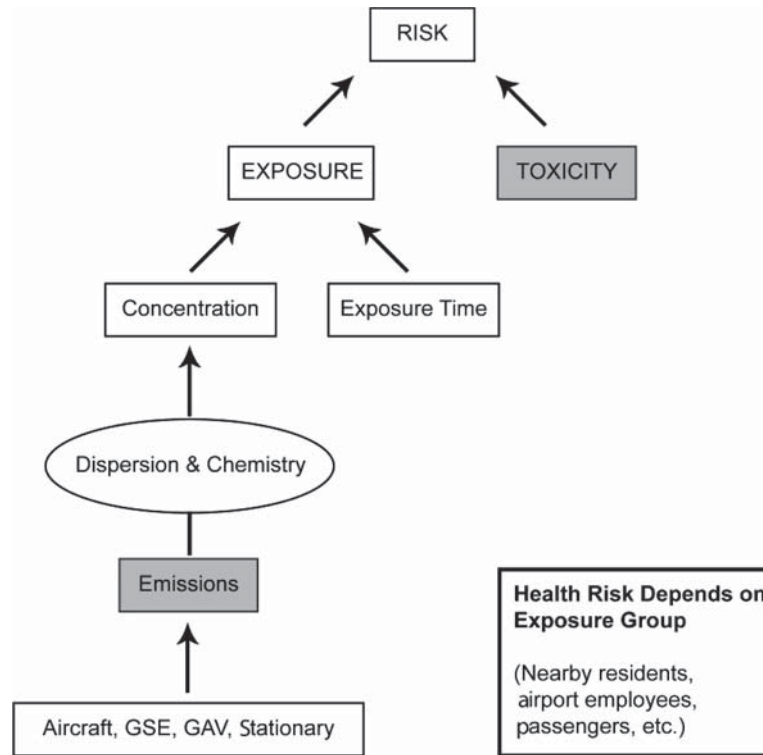
Figure 1. Schematic depiction of the factors that determine risk. *Emissions of pollutants from various sources undergo chemistry and dispersion in the atmosphere to determine a concentration. Risk is determined by the toxicity of these pollutants and the total exposure. This report focuses on emissions and toxicity, rather than exposure and toxicity, since to a first approximation total exposure due to a given source is proportional to emission rates, which are much easier to quantify and less situation-specific. There is also a "background" concentration of most pollutants that is determined by regional to global processes.*

disadvantage of the approach is that exposure is essential for determining true risk of any population, and thus, the approach identified in this report would not enable identification of absolute human health risk at any airport. Rather, this preliminary assessment is intended to guide the identification of information gaps and the formation of a prioritized research agenda, as noted below.

The greatest source of airport-related source gas-phase HAPs is aircraft operations, as described in Section 3 of this report. As a result, this report focuses on the current state of knowledge regarding HAPs emitted by aircraft and the associated information gaps. In Section 2 the emissions and toxicity-weighted relative rankings of HAPs emitted by aircraft and GSE are described. In subsequent sections the state of knowledge regarding emissions from the various airport-related sources (e.g., aircraft, auxiliary power units, GAVs, stationary

sources, and GSE) and the toxicity of these emissions are discussed.

1.5 Main Findings

The research team reported the following findings:

1. Aircraft emissions at idle/taxi power are the predominant source of significant gas-phase HAP emissions at an airport. The actual emissions can vary by more than a factor of two depending on the actual power thrust levels used (e.g., real-world ground idle versus International Civil Aviation Organization [ICAO] 7% idle), time spent idling, and ambient conditions, especially temperature. (Yelvington, Herndon et al. 2007). It is likely that many current airport emission inventories underestimate aircraft HAP emissions as the
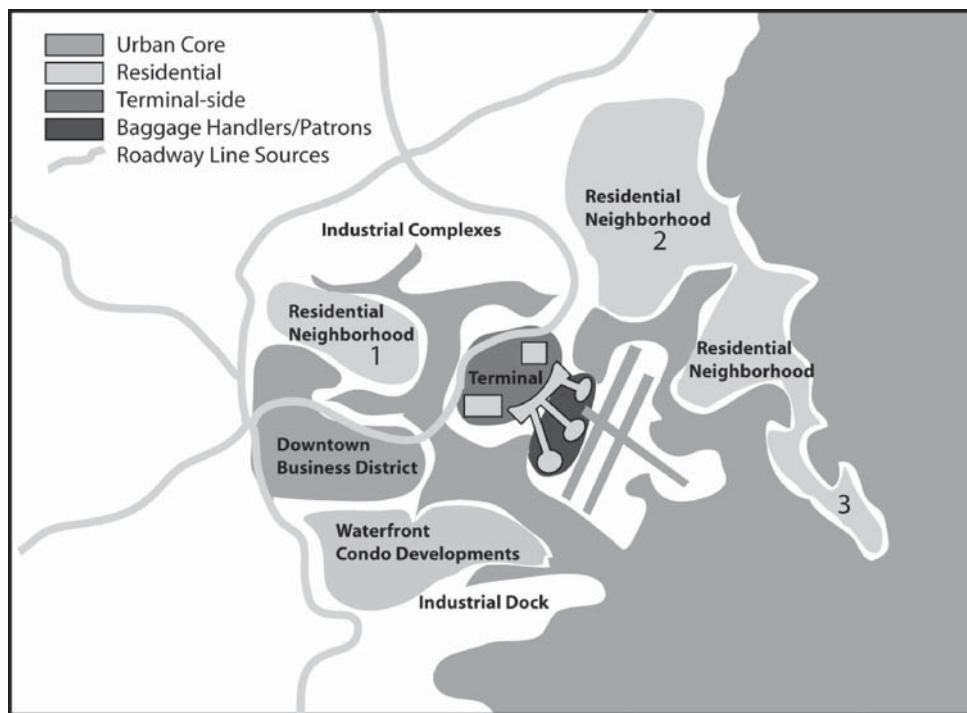
Figure 2. Map of a hypothetical airport. *The factors that determine risk for any given exposure group depend on numerous factors such as the proximity of emission sources to the location of exposure.*

required emissions and dispersion modeling system (EDMS) assumes use of 7% thrust during the idle and taxi phase (HAP emission rates are higher at lower thrust levels).

2. Consideration of both the quantity of emissions and the toxicity of the individual pollutants yields a list that ranks the relative importance of airport-related HAPs. This list is similar to those produced by two previous studies for many compounds (acrolein, benzene, 1,3-butadiene, etc.), but differs significantly for others (e.g., toluene, xylene). The compounds in Table 1 are listed in order of relative im-

portance. This ranking reflects that some HAPs emitted in great quantity have relatively low toxicity, while other HAPs emitted in lower quantities have high toxicity. The "rank" of formaldehyde on the list prepared for this report depends on which of two values is used for its inhalation unit risk (IUR). Use of the value currently listed on EPA's Integrated Risk Information System (IRIS) database results in the placement as shown in Table 1 (i.e., second only to acrolein in importance). Use of the value by the Chemical Industry Institute of Toxicology (CIIT), which is used by

Table 1.   Comparison of aviation-related HAPs lists.

This ACRP Review	FAA 2003	ORD 2005
Acrolein	Formaldehyde	Acrolein
Formaldehyde*	Acetaldehyde	1,3-Butadiene
1,3-Butadiene	Benzene	Formaldehyde
Naphthalene	Toluene	Benzene
Benzene	Acrolein	Acetaldehyde
Acetaldehyde	1,3-Butadiene	Naphthalene
Ethylbenzene	Xylene	Toluene
	Lead	
	Naphthalene	
	Propanal (Propionaldehyde)	

Notes:
HAP   hazardous air pollutant
FAA   Select Resource Materials and Annotated Bibliography on the Topic of Hazardous Air Pollutants
             (URS 2003)
ORD   O'Hare Modernization Environmental Impact Statement (FAA 2005)

* Using EPA IRIS value

the EPA's National Air Toxics Assessment, results in a much less significant role for formaldehyde.

Table 2 lists additional HAPs identified by this analysis that may also be important to consider for further evaluation. These HAPs have not undergone a formal toxicity evaluation. A comparison with structurally similar HAPs, however, indicates they may be important in terms of relative toxicity and emissions. Note that glyoxal and methylglyoxal are currently not classified by the EPA as HAPs, but are included on the EPA's "Master List of Compounds Emitted by Mobile Sources." This analysis indicates they may be among the most important airport HAPs.

3. The two gas-phase HAPs for which non-aircraft sources (GSE, GAV, and stationary sources) are most important, when viewed in the same type of emissions-toxicity weighting, are benzene and 1,3-butadiene, both of which are primarily emitted by gasoline engines (as opposed to those that run on diesel or compressed natural gas).

4. Speciation profiles for aircraft-emitted HAPs that were based on the work of Spicer, Holdren et al. (1994) are accurate, as the relative speciation of HAPs in aircraft exhaust has been found to be constant among numerous types of engines subsequently characterized (see Section 5.1). Recent field measurements (EXCAVATE, APEX 1, 2, 3) have greatly expanded the knowledge base regarding the quantification and speciation of aircraft HAPs emissions.

1.6 Prioritized Research Agenda

Based on the results of this research, the following areas of research have been identified that would be most beneficial in addressing these information gaps. The projects listed below should be able to address the identified information gaps and substantially decrease the uncertainty associated with airport-related HAPs. More detail is presented in Section 9.

Research Item 1: Identify the effects of ambient conditions (temperature, pressure, humidity) and engine technology on HAP emissions at various idle/taxi power settings.

This project would measure the emission rates of various HAPs compounds from commercial aircraft as a function of thrust level near idle and as a function of environmental variables such as temperature, humidity, and pressure. The goal of this project would be to improve our quantitative understanding of the largest airport-related HAPs emission source—jet engines operating at low power. Emissions data for commercial aircraft are only available in the narrow temperature range (8° to 35°C, 46° to 95°F), and show that HAP emissions increase greatly with decreasing temperatures. The lack of knowledge regarding the temperature dependence of HAP emissions, and how it depends on engine technology, currently results in uncertainties of more than a factor of 2 in modeled HAP concentrations and risk. This is especially important for airports located in cold environments.

Research Item 2: Quantification of the "real-world" thrust values used at airports during the idle phase.

This project would investigate and quantify the actual thrust values used by commercial aircraft at several airports. Recent research indicates that the standard power setting (7% rated thrust) that is used to calculate emission inventories does not represent actual thrust levels used during aircraft taxi and idle. This introduces large uncertainties in emission inventories and risk assessment, since HAP emissions are very sensitive to small changes in engine power.

Table 2. Aviation-related HAPs of potential concern.

HAP	Basis for Concern
Crotonaldehyde	Crotonaldehyde is structurally similar to the highly reactive compound acrolein, and its airport emissions may be comparable to those of benzene and 1,3-butadiene.
Glyoxal	Glyoxal is a mutagenic aldehyde with two carbonyl groups, and has been shown to act as a tumor promoter in rats. Airport emissions of glyoxal are comparable to those of benzene and 1,3-butadiene.[a]
Methylglyoxal	Methylglyoxal is a mutagenic aldehyde with two carbonyl groups that has a DNA adduct formation potency 20-fold greater than acetaldehyde. Airport emissions of methylglyoxal are comparable to those of benzene and 1,3-butadiene.[b]
Propanal (propionaldehyde)	Propanal (propionaldehyde) is structurally similar to acetaldehyde and its emissions are comparable to naphthalene.

[a] IARC 1991; NEG 1995.
[b] IARC 1991; Vaca, Nilsson et al. 1998.

Research Item 3: Characterization of HAP emissions from general aviation (e.g., piston engine aircraft).

This project would support emissions measurements of general aviation aircraft. HAP emissions (with the exception of lead) from piston engine aircraft, turbojet engines, and low-bypass turbofan engines (such as business jets) are largely unknown and should be quantified. This is most important at general aviation airports.

Research Item 4: Identify the emission sources most important to on-airport and off-airport exposure.

The purpose of this project is to identify which emission sources (aircraft, GSE, terminal traffic, etc.) most greatly affect potential receptors (e.g., nearby residents, airport-based workers, passengers). This should be done using dispersion/chemistry models tested against complementary measurements. Conclusive deduction of source apportionment will require coordinated measurements of the main combustion gases (CO_2, CO, NO, NO_2), speciated HAPs (e.g., benzene, formaldehyde, etc.) and particulate matter (PM) (characterized by number/size, mass, and chemical composition). Source apportionment is required to evaluate proposed emissions mitigation strategies. This project will help airport operators to identify the "low-hanging fruit" with regards to minimizing the health risk presented by the various emission sources present at an airport.

SECTION 2

Integration of Emission Rates with Toxicology—Prioritization of Airport Hazardous Air Pollutants

The central goal of this project is to produce a prioritized research agenda that addresses shortcomings in our knowledge related to airport-related HAPs. The current ability of researchers, airport operators, consultants, and others to assess the health risks associated with human exposure to aviation-related HAPs relies on a number of criteria including the sources, toxicity, and chemistry of HAPs.

One activity that will greatly assist in this goal is to identify which pollutants to consider as aviation-related HAPs and rank their relative importance. In general terms, this report intends to provide a screening-level analysis of the volatile organic compounds (VOCs) emitted at airports in order to help prioritize compounds that might pose an inhalation risk to people at or near the airport. This risk is a function of the toxicity of each molecular species and the extent of exposure to this species. Total human exposure is a complex function of emissions, chemistry, dispersion, length of exposure, location, and affected population and is not easily condensed into a simple formula (see Figure 1 in Section 1.4).

To determine which sources are the most important, one must know what exposure group is of interest. Airline passengers are in closest proximity to GAV emissions while traveling to and from the airport, and spend a few hours inside the airport buildings and several hours inside the aircraft cabin itself. Residents of nearby communities are likely in closest proximity to either GAV or to aircraft themselves, depending on the geographic configuration of the roads, airfield, and housing. Airport employees can be in close proximity to virtually all airport-related sources. As shown previously in Figure 2's map of a hypothetical airport, some communities near the hypothetical airport are closest to the airfield, while other nearby communities are closest to the roadside traffic. Evaluation of which source is most important for each possible exposure group must be done on a case-by-case basis, and this report does not attempt to do so. Instead this report only examines overall airport-related emissions.

The FAA adopted a related but simpler approach to develop a list of airport-related HAPs compounds in a recent review of HAPs emissions (URS 2003). FAA selected the HAPs compounds that are emitted in largest quantity in airport-related activities. This approach resulted in their tabulation of 10 aviation-related HAP compounds on the basis of mass emission rates (see Table 1, second column). The relative toxicity of the compounds was not directly considered. The difficulty with that approach is that the relative toxicities of the various compounds have the potential to vary far more than their emission rates. A strength of that approach is that the methodology is simpler since many of the toxicity factors are uncertain.

The approach used in this report is to weigh the importance of HAPs by both their relative emission rate and toxicity, even though the toxicological data are clearly incomplete. Estimates of relative HAP emissions can be made as a function of molecular species for the various sources present at airports. As discussed in the next section, the most important source of most airport gas-phase HAPs is the aircraft themselves. Furthermore, the vast majority (> 90%) of aircraft HAP emissions occur when aircraft are taxiing or idle. This report therefore focuses primarily on this HAPs source (aircraft idle/taxi emissions) to generate a list of the most important aviation-related HAPs compounds. This list is supplemented where appropriate with information regarding emissions from airport stationary sources, GAV, or GSE.

In Table 3, the *relative* priority of more than 50 organic species that are emitted by aircraft turbine engines and GSE are calculated. The first column identifies the compounds. The second and third columns give risk-based concentrations (RBC) for each species if available. The RBCs in the second column reflect noncarcinogenic health risks while those in the third column are derived from estimates of cancer risk. There is a detailed discussion of the sources and methods used to estimate the RBCs later on in Section 4. The RBCs

Table 3. Toxicity-emissions weighting of HAPs emitted by airport sources.

Compound	RBC noncancer	RBC cancer	Min RBC (mg/m^3)	Aircraft EI(x)/EI(HCHO)	GSE EI(x)/EI(HCHO)	Aircraft Relative Impact	GSE Relative Impact
methane				0.227			
ethane				0.042			
ethene[1]				1.256			
	2.1E+03	9.2E-01	**9.2E-01**			1	
propane				0.006			
acetylene				0.32			
propene	3.1E+03		**3.1E+03**	0.368		0	
1-butene	3.1E+03		**3.1E+03**	0.142		0	
1,3-butadiene	2.1E-03	8.1E-05	**8.1E-05**	0.137	0.059	1689	727
c2-butene				0.017			
1-pentene	3.1E+03		**3.1E+03**	0.063		0	
n-pentane	1.9E+01		**1.9E+01**	0.016		0	
2,2,4-trimethylpentane	1.9E+01		**1.9E+01**	0 to 0.1		0	
C5-ene				0.029			
2-methyl-2-butene				0.015			
C5-ene				0.022			
2-methylpentane	1.9E+01		**1.9E+01**	0.033		0	
1-hexene				0.06			
	6.5E-01		**6.5E-01**			0	
benzene	1.0E-02	3.1E-04	**3.1E-04**	0.137	0.378	439	1210
1-heptene				0.036			
n-hexane	7.3E-01		**7.3E-01**	~0.01	0.062	0	0
n-heptane	1.9E+01		**1.9E+01**	0.005		0	
toluene	5.2E+00		**5.2E+00**	0.052	0.450	0	0
hexanal				0.014			
1-octene				0.022			
n-octane	1.0E-01		**1.0E-01**	0.005		0	
ethylbenzene	1.0E+00	9.7E-04	**9.7E-04**	0.014	0.119	14	122
m,p-xylene	1.0E-01		**1.0E-01**	0.023	0.403	0	4
styrene	1.0E+00		**1.0E+00**	0.025	0.007	0	0
o-xylene	1.0E-01		**1.0E-01**	0.023		0	
1-nonene				0.02			
n-nonane	1.0E+00		**1.0E+00**	0.005		0	
phenol	2.1E-01		**2.1E-01**	0.016		0	
1-decene				0.015			
n-decane	1.0E+00		**1.0E+00**	0.026		0	
C4-benzene				0.018			
n-undecane	1.0E+00		**1.0E+00**	0.036		0	
C5-cyclohexane				0.021			
C5-benzene				0.017			
naphthalene	3.1E-03	2.4E-05	**2.4E-05**	0.044		1808	
naphthalene		7.2E-05	**7.2E-05**	0.044		615	
n-dodecane	1.0E+00		**1.0E+00**	0.035		0	
C13-alkane	1.0E+00		**1.0E+00**	0.014		0	
C14-alkane	1.0E+00		**1.0E+00**	0.014		0	
2-methyl naphthalene	2.1E-01		**2.1E-01**	0.017		0	
1-methyl naphthalene	2.1E-01		**2.1E-01**	0.02		0	
formaldehyde	0.01	1.9E-04	**1.9E-04**	1	0.150	5342	801
formaldehyde	0.01	4.4E-01	**1.0E-02**	1	0.150	100	15
acetaldehyde	4.1E-01	1.1E-03	**1.1E-03**	0.347	0.029	314	27
acetaldehyde	9.4E-03	1.1E-03	**1.1E-03**	0.347	0.029	314	27
acrolein	2.1E-05		**2.1E-05**	0.293	0.002	14048	99
propanal				0.059	0.072		
acetone	3.2E+01		**3.2E+01**	0.03		0	
butanal	4.1E-01	1.1E-03	**1.1E-03**	0.078		71	
benzaldehyde				0.038			
glyoxal				0.148			
methylglyoxal				0.122			
dimethylnapthalene	2.1E-01		**2.1E-01**	0.01		0	
other PAHs		4.4E-05	**4.4E-05**	0.001		23	
crotonaldehyde				0 to 0.1			

listed in the fourth column are the smaller (higher risk) of those listed in columns two and three. The fifth column lists the emission ratios for each molecular species for a CFM-56 turbine engine operated at idle. The emission ratio is expressed as the mass emission rate of each species divided by that of formaldehyde. EI(x)/EI(HCHO) means emission index of species "X" divided by the emission index of formaldehyde. For example, the mass emission rate of 1,3-butadiene is equal to 13.7% of the mass emission rate of formaldehyde. The choice of formaldehyde as a reference is due to its abundance in aircraft exhaust and its commonality across different measurement efforts. The emission factors are taken from Spicer, Holdren et al. (1994). More recent datasets (EXCAVATE, APEX, etc.) have mostly confirmed the relative speciation of Spicer and have found that the speciation is fairly constant among the ~10 engines that have since been characterized. These topics will be discussed in Section 5. The sixth column lists emission factors for GSE HAPs scaled to the aircraft source so that aircraft and GSE emissions may be compared. This scaling is based upon the formaldehyde emission inventories from three airports: Fort Lauderdale-Hollywood International Airport (FLL), Philadelphia International Airport (PHL), and Chicago O'Hare International Airport (ORD), all of which indicate that formaldehyde emissions from GSE are equal to 15% ± 3% of the aircraft formaldehyde source. Thus, the GSE formaldehyde emission ratio was set equal to 0.15 in the table and the values for the other HAPs were set relative to this value using the EPA's speciation profile for nonroad mobile sources. Finally, in columns seven and eight are the ratios of the source-specific emission factor to the minimum RBC for each species. These quantities are proportional to overall health risk but are not intended to have absolute significance.

The result of this exercise is a list of the most significant HAPs species emitted by aircraft and GSE in the immediate vicinity of airports. Similar calculations for GAV and stationary source emissions, when only considering vehicle miles traveled within the airport perimeter, show that these emissions are minor compared to the aircraft emissions (and in some cases GSE emissions). The species with the largest "relative impact" values in columns 7 and 8 are taken to be the most significant aviation-related HAPs species. This estimate is, of course, limited by our incomplete knowledge of the input parameters. This is particularly true for the RBCs, which are uncertain for many species. Nevertheless, the result of this exercise is important since it challenges the conventional view of which species are of highest priority for future studies. The alternative is to ignore the toxicology, which is equivalent to assuming that all species carry equal risk. By considering the emissions and toxicity (the combined approach using toxicity values described previously), the ranking of the five most important airport-related gas-phase HAPs is: (1) acrolein, (2) formaldehyde,

(3) 1,3-butadiene, (4) naphthalene, and (5) benzene. Of these compounds, the only ones for which non-aircraft sources are important are 1,3-butadiene and benzene, for which GSE emissions may be comparable to the aircraft source. This is only the case for airports in which GSE emissions of VOCs (by mass) are comparable in magnitude to VOC emissions by aircraft—though the trend of decreasing GSE emissions due to fleet improvements (see Section 5.2.2) is making this scenario less common. Emissions due to stationary sources and GAV within the airport perimeter are minor compared to the aircraft, as discussed in Section 3. Formaldehyde is included as one of the most important HAPs when using the inhalation unit risk (IUR) currently listed in the EPA's IRIS database; while use of the value developed by the CIIT, which is used by the EPA's National Air Toxics Assessment, results in a surprisingly less significant role for formaldehyde. That is, the relative importance of formaldehyde depends greatly on which value is considered for its IUR.

Several rows in Table 3 are highlighted. Compounds highlighted in light grey are found to be significant airport-related HAPs and have been generally regarded as such in other studies. "Significant" in this context means these compounds have a high *relative* importance when using this combined emissions-toxicity weighting. Compounds highlighted in dark grey—glyoxal, methylglyoxal, and crotonaldehyde (butenal)—have the potential to be significant airport-related HAPs but are not generally included in other lists. None of these three compounds is currently included on the EPA's list of 188 hazardous air pollutants (as dictated by the Clean Air Act), but are included in the EPA's "Master List of Compounds Emitted by Mobile Sources" (www.epa.gov/otaq/toxics.htm). It is noted that the emission factors for these three species (especially crotonaldehyde) are more uncertain than the other compounds since they are difficult to measure, and the relevant toxicological information is incomplete. Their importance depends on their toxicity and confirmation that they are emitted at the levels estimated in Table 3. Finally, two compounds—toluene and the xylene isomers—highlighted in the table with a dotted background, are found to have a surprisingly low relative ranking by this emissions-toxicity weighting but are included on other lists of aviation related HAPs. These compounds are emitted in large quantities, yet existing toxicity information indicates they present much less of a health risk than other HAPs with comparable emissions, such as acrolein or benzene. The details of their toxicology are discussed below in Section 4. This prioritization does not account for acute effects (Section 4.4), which can be very compelling in terms of lost work days and accidents.

These differences were summarized in Table 1 where the most significant HAPs species identified in this review are compared to two other reports. The first report is a recent FAA

review (UCR 2003) that compiled a list of aviation-related HAPs ranked in order of overall emission rate (without regard to toxicity). The other source is a recent Chicago O'Hare International Airport (ORD) Environmental Impact Statement (EIS) (FAA 2005). The ORD document used an approach similar to the one adopted in this report, using toxicity and emission rate as the key criteria.

As discussed above, the approach recommended by this ACRP project team is that prioritized aviation-related HAPs be determined by comparing estimated relative emissions with RBCs. Using this prioritization scheme, HAPs with greater emissions and lower RBCs (i.e., higher toxicity) are given greater weight. Although the ORD EIS considered toxicity, it used a different approach for weighting relative toxicity than that used in this review. For example, the ORD EIS gave carcinogens classified as "known" or "probable" human carcinogens more weight than "possible" carcinogens, whereas all carcinogens were weighted equally (relative to their potency) in our approach. Neither this report nor the ORD EIS relied exclusively on toxicity criteria available on EPA's IRIS database. Finally, the ORD EIS used a different approach for weighting carcinogens versus noncarcinogens.

Of note on our list of high-priority HAPs is the absence of toluene. Although toluene emissions are relatively high, the toxicity is relatively low. EPA considers that the confidence in the reference concentration for toluene, as well as the underlying database, is high (USEPA 2005b). Carcinogenicity of toluene has been evaluated by the National Toxicology Program in both rats and mice, with no convincing evidence that toluene is carcinogenic. In addition, toluene does not appear to be genotoxic (i.e., it does not directly cause DNA damage).

As discussed previously, glyoxal, methylglyoxal, and crotonaldehyde may be important HAPs for further evaluation as well. These HAPs have not undergone a formal toxicity evaluation. However, a comparison with structurally similar HAPs indicates they may be important in terms of relative toxicity and emissions. This analysis indicates they may be among the most important airport HAPs pending determination of their toxicity.

Subsequent sections contain more details concerning the state of the toxicological data and a detailed rationale for our decision to focus on HAP emissions from aircraft turbine engines operating near idle as the dominant source of HAPs at commercial airports.

SECTION 3

Relative Contribution of Airport-Related Volatile Organic Compound Emissions

This section discusses the relative contribution of different airport emission sources to total gas-phase HAP emissions. Emissions of pollutants from airports are quantified in emission inventories. Airports are often required to generate an emission inventory for environmental impact statements prepared for airport expansions under the National Environmental Policy Act (NEPA), and/or to enable FAA to approve federal actions occurring in nonattainment and maintenance areas where the FAA must show that the federal action conforms to the State Implementation Plan.

In a broader sense, quantifications of emissions data (which rely on measurements) are used with predictive computer models such as the EDMS, so that ambient concentrations can be predicted. Any computational model whose purpose is to predict the concentration of pollutants relies on various inputs such as emissions data (e.g., grams of NO_x emitted by aircraft during one of the LTO cycle modes) and meteorology (e.g., wind speed and direction). The use of emissions data, predictive models, and measurements of ambient concentrations are complementary activities. Emissions data by themselves (e.g., emission indices) do not predict or determine ambient concentrations (and risk). Use of emissions data, ambient concentration measurements, and models together is ideal—the measurements can validate the predictions of the model, the model provides information on which emission sources matter most, and if validated the model can, in some cases, be used to predict concentrations.

In this report airport sources are divided into four main categories:

1. Aircraft,
2. Auxiliary power units and ground support equipment (APU/GSE),
3. Ground access vehicles (GAV), and
4. Stationary sources.

The relative contribution of these four emission categories for Philadelphia International Airport are shown in Figure 3.

Most airport emission inventories classify emission sources into identical or similar categories. The emission and activity factors from each of these sources will be discussed later in this report, with the most emphasis placed on aircraft emissions for two main reasons:

1. The research reviewed indicates that aircraft emissions are currently the dominant source of gas-phase HAPs when using a toxicity-emissions weighting method. This observation will be discussed at length in this section.
2. The aircraft emissions category is the category for which the knowledge base of PM and HAPs has increased the most in the past few years thanks to recent field campaigns.

The first point above is based on the following pieces of information:

1. Most airport emission inventories currently report that aircraft at idle/taxi are the biggest source (in tons per year) of gas-phase HAPs. This is quantitatively discussed for ORD, PHL, and FLL later in this section (see Tables 4 and 5). Similar conclusions can safely be made for the airports of Washington, D.C. (Dulles), Boston, San Diego, and Long Beach based on their emission inventories (DOT and FAA 2005, Vanasse Hangen Brustlin 2006, San Diego International Airport 2006, City of Long Beach 2005).
2. Weighting the relative importance of the various emission sources based on both mass emission rates and toxicity of the emitted gas-phase HAPs further increases the importance of aircraft emissions relative to the other airport sources. This is because aircraft VOC emissions contain a higher fraction of the most toxic HAPs such as acrolein, 1,3-butadiene, and formaldehyde (compared to GSE, which constitutes the second biggest source of emissions-toxicity-weighted gas-phase HAPs). Stationary sources are minor sources of HAP emissions (though in some cases they contribute greatly to total VOC emissions). This is
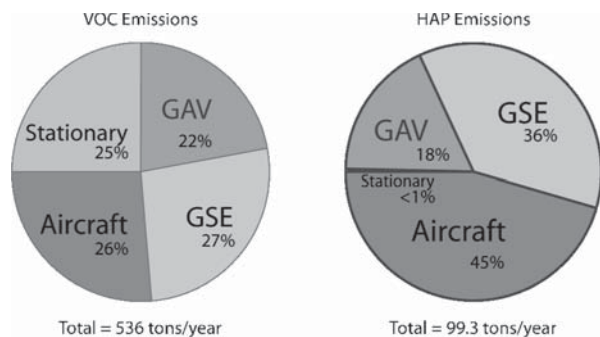
Figure 3. Emission inventory for PHL. The pie chart on the left depicts total VOC emissions from the four emission sources. The pie chart on the right depicts only the emissions of the 10 HAPs considered in the PHL environmental impact statement.

visually portrayed for PHL in Figure 4. A report on emissions from Santa Monica Municipal Airport, that only considered benzene, formaldehyde, 1,3-butadiene, and acetaldehyde came to a related conclusion: that aircraft at taxi/idle were the dominant source of carcinogenic risk (Piazza 1999).

3. It is highly likely that the actual emissions of gas-phase HAPs by aircraft are underestimated (due to the current lack of data) in these reports—perhaps by a factor of two or more. This is due to two reasons: (a) the assumed use of 7% power level for aircraft idle underestimates actual HAPs emissions since commercial aircraft often idle at lower thrust settings resulting in much higher emission rates of HAPs, and (b) the HAP emission rates from aircraft engines at idle are much greater at low ambient temperatures and this temperature dependence is not reflected in emission inventories.

4. Many airports (especially those in nonattainment areas) have had success in reducing emissions from GSE, and the action required to reduce GSE emissions is fairly straight-

forward—upgrade the GSE fleet (e.g., to run on compressed natural gas [CNG] or electricity, see Section 5.2.2). In contrast, the most appropriate methods to reduce aircraft emissions are not as straightforward.

Ground access vehicles (GAV) only make an appreciable contribution to total airport gas-phase HAP emissions in emission inventories when off-airport miles driven are considered (as is required for some environmental impact statements). Even when off-airport miles driven are considered, aircraft are never a minor source of overall HAP emissions (see Figures 3 and 4).

These four topics are discussed in the remainder of Section 3. It is reemphasized that although gas-phase HAP emissions are dominated by aircraft at idle/taxi, the human health risk presented by the various emission sources at an airport depends on many factors such as particulate matter emissions, the exposure group, the physical layout of the airport, and the local meteorology.

The relative importance of the four main emission sources are first compared for Philadelphia International Airport (PHL) in a series of pie charts (Figures 3 through 5) before looking in greater depth at a few more airports. The contributions of the four main emission sources to VOC emissions and gas-phase HAP emissions (consisting of formaldehyde, toluene, xylene, benzene, acetaldehyde, 1,3-butadiene, ethylbenzene, acrolein, naphthalene, and lead) at PHL are displayed in Figure 3.

Figure 3 displays the emission rates of all 10 HAPs combined. If only on-road vehicle miles that occurred within the airport perimeter were counted, the GAV contribution would be smaller. When weighted by the toxicity criteria (see Figure 4), it is seen that the importance of the aircraft and GSE source increases, while the importance of stationary sources almost vanishes. This is because alkanes, which are the predominant type of VOCs emitted by stationary sources, are not very toxic. The IRIS toxicity value for formaldehyde was

Table 4. Total volatile organic compound emission profiles.

Source	BOS 2005		PHL 2003		FLL 2005		ORD 2002	
	tons/yr	%	tons/yr	%	tons/yr	%	tons/yr	%
Aircraft	240	47	141	26	155	32	424	21
GSE/APU	71	14	142	26	137	28	414	20
GAV	47	9	118	22	154	31	1,149	57
Stationary	156	30	134	25	46	9	34	2
Total	514	100	536	100	492	100	2,021	100

Notes:
BOS   Boston Logan International Airport (Vanasse Hangen Brustlin 2006)
PHL   Philadelphia International Airport (KM Chng Environmental 2005)
FLL   Fort Lauderdale-Hollywood International Airport (Landrum & Brown 2007)
ORD   Chicago O'Hare International Airport (FAA 2005)
tons/yr   tons per year
GSE/APU ground support equipment/auxiliary power unit
GAV   ground access vehicles

Table 5. Emission inventory for selected hazardous air pollutants.

HAP	Aircraft	GSE/APU	GAV	Stat
Philadelphia International Airport (PHL) (tons/yr)				
Benzene	3.3	7.24	2.3	0
Formaldehyde	24.5	3.2	2.2	0.2
1,3-butadiene	2.9	1.2	0.4	0
Acrolein	3.7	0.12	0.1	0
Toluene	1.1	11.1	6.6	0.1
Fort Lauderdale-Hollywood International Airport (FLL) (tons/yr)				
Benzene	8.7	7	0	0
Formaldehyde	66.6	10.7	2.7	0.4
1,3-butadiene	8.1	1.1	1.5	NA
Acrolein	8.7	0.4	1.8	NA
Toluene	3.8	8.0	1.1	1.8
Chicago O'Hare International Airport (ORD) (tons/yr)				
Benzene	6.4	20.3	40	0
Formaldehyde	38.8	7.4	16.0	0.1
1,3-butadiene	10.5	4.2	4.8	NA
Acrolein	1.1	0.3	0.7	NA
Toluene	3.2	38.1	95.6	0
Notes : HAP hazardous air pollutant Air aircraft GSE ground support equipment GAV ground access vehicles Stat stationary sources tons/yr tons per year NA not available (negligible)				
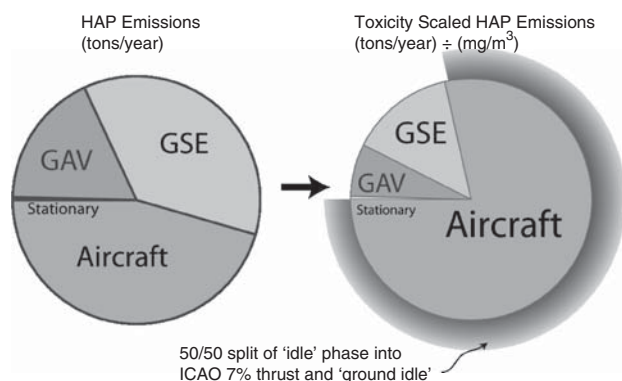
Figure 4. Comparison of PHL HAP emissions scaled by mass and by mass-toxicity. Weighting the emissions by the toxicity of the 10 HAPs considered indicates that the aircraft are the predominant source of the most important HAPs. The largest wedge represents the HAP emissions as calculated using 7% thrust for the idle phase. The extra "shell" around the aircraft wedge represents a 60% increase in HAP emissions as calculated by assuming that idle thrust is an equal mix (in time) of 7% thrust and 4% thrust. The actual thrust levels used by aircraft are one of the biggest information gaps identified in this report, and result in uncertainty of the aircraft contribution to gas-phase HAPs by at least a factor of 2.

used for Figure 4. The PHL emission inventory was calculated using 7% thrust for the power level used during aircraft idle/taxi, as this is the certification value for idle thrust used by the International Civil Aviation Organization (ICAO). Use of a lower, more realistic thrust level (i.e., "ground idle") results in much higher emission rates (see Section 5.1). The "extra" area near the aircraft wedge in Figure 4 represents a 60% increase of gas-phase HAP emissions, assuming that during idle/taxi the aircraft spends equal amounts of time at 7% thrust and 4% thrust. The true distribution of thrust levels used during aircraft idle/taxi is highly uncertain (i.e., how much time is spent at different thrust levels).

Figure 5 compares the total mass emission rates of the 10 individual HAPs to the toxicity-weighted emissions without regard to the emission source (e.g., aircraft versus GSE). The most important airport-related gas-phase HAPs are acrolein, 1,3-butadiene, and benzene. Aircraft are the biggest emitters of acrolein, 1,3-butadiene, and formaldehyde, whereas gasoline GSE can be the biggest source of benzene. This calculation used the IRIS toxicity for formaldehyde, although use of the IRIS value does not appreciably change the figure.

3.1 Source Apportionment

In this section the relative importance of the various airport emission sources is discussed quantitatively in more detail using the emission inventories of three major airports: Philadelphia, Fort Lauderdale, and Chicago O'Hare (KM
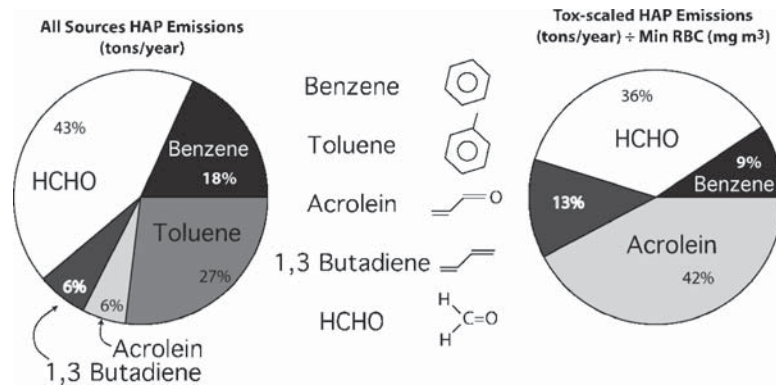
Figure 5. Comparison of total HAP emissions at PHL by mass and by mass-toxicity. *Relative risk presented by the 10 HAPs considered in the PHL environmental impact statement. The risk is calculated by consideration of both total mass emissions and toxicity criteria.*

Chng 2005; Landrum and Brown 2007; and FAA 2005). These emission inventories were all made as part of environmental impact statements pursuant to the National Environmental Policy Act (NEPA) and were created used the FAA's Emissions Dispersion Modeling System, as required.

The total VOC emissions reported by these four airports are compared in Table 4. Table 5 displays the reported emission inventory for five selected gas-phase HAPs from three of the four airports. The five HAPs selected (benzene, formaldehyde, 1,3-butadiene, acrolein, and toluene) have traditionally been considered to be among the most important air toxics and other studies have focused on these compounds (e.g., Piazza 1999; FAA 2005).

Tables 4 and 5 form the basis for the discussion of source apportionment.

3.1.1 Overall Source Apportionment

At BOS, the aircraft category is the biggest source of VOCs, whereas PHL and FLL's inventories gave roughly equal weight to the four main categories. ORD, meanwhile, only attributes 21% of VOC emissions to aircraft due to the large fraction for which GAV account. This is at least in part due to ORD's inclusion of GAV emissions outside of the airport proper as was needed based on the purpose of the emissions inventory.

HAP emissions are not necessarily proportional to total VOC emissions, however. Indeed as seen in Table 5, aircraft are reported to be the greatest source of formaldehyde, 1,3-butadiene and acrolein at all four airports, even those in which aircraft are not reported as the biggest source of VOCs. PHL's full inventory states that aircraft account for well over 50% of emissions of the following additional HAPs: acetaldehyde; naphthalene, propionaldehyde, styrene, and polycyclic

organic matter (POM) (as 16-PAH). Similarly, FLL EIS states that aircraft only account for ~25% of total VOC emissions, but still account for more than 50% of the emissions for most of the compounds listed above. If these inventories are correct, then aircraft appear to be the greatest airport source (in tons per year) of most air toxics, with the most noticeable exceptions above being benzene and toluene. At ORD, aircraft only account for 10% of benzene emissions. But as shown below, this estimate includes off-airport emissions from GAV. The fractional contribution of aircraft to benzene emissions that occur at the airport is likely much greater.

In summary, for PHL, FLL, and ORD, aircraft are the biggest overall emitters of gas-phase HAPs when only emissions within the airport perimeter are considered. Of note is that reported VOC and HAP emissions at FLL are comparable to those at PHL and ORD even though activity levels (e.g., number of flights) at FLL are significantly lower than PHL and ORD. The explanation for this is currently unclear.

3.1.2 Ground Access Vehicles

There is great variation among inventories in the treatment of GAV emissions. While there can be significant differences in the vehicle fleets and number of vehicle visits among the airports, the distance to which vehicle miles are counted as part of the airport inventory is the biggest variable. GAV account for only 3% of total VOC emissions in the IAD (Washington Dulles Airport, not shown) inventory mainly because only on-site vehicle miles are included. Airport-related miles driven on the connecting highways/roadways are explicitly excluded because they are already included elsewhere in the Transportation Improvement Plan for Fairfax and Loudoun counties and a redundancy was undesirable (DOT, FAA et al. 2005). In contrast, Portland International

Airport (PDX, not included above) counts vehicle miles driven up to a distance of 35 miles from the airport, and not surprisingly attributes 50% of its total VOC emissions to GAV (S. Hartsfield, personal communication). Similarly, the ORD EIS emissions inventory accounted for vehicle miles driven on a geographic area that extends well beyond the bounds of the airport grounds. Such drastic differences are not flaws in any inventory, but do underscore the wide variation in methodologies and the need to interpret such data in context. Not all emission inventories attempt to answer the same questions and these differences are most often associated with the purpose of the emissions inventory. Consider the following questions:

- What are the total emissions associated with the existence of the airport?
- What change in emissions would be associated with a given construction/upgrade project at an airport?
- What are the total emissions that come from within the airport perimeter?

This report focuses on aircraft emissions for the reasons discussed in Section 3.

3.1.3 Stationary Sources

Stationary sources such as evaporative emissions from fuel storage, HVAC systems, and generators account for 25% to 30% of reported VOC emissions at BOS and PHL, but are only reported at a minor 2% at ORD. This is one of many potential discrepancies among the self-reported airport emissions that could be elucidated if accurate fuel use inventories were available (Section 3.1.5). At PHL, evaporative emissions account for less than 1% of the total emissions for all 16 toxic pollutants (HAPs) listed in its environmental impact statement, including benzene. One of the few HAPs for which stationary sources can constitute a nontrivial source is toluene, for which FLL attributes 12% due to painting activities. As discussed later in this report, the toxicity of toluene is low compared to other gas-phase HAPs emitted at airports. The speciation of evaporative emissions is very different from that for exhaust sources. Evaporative emissions contain a high fraction of alkanes, which are both relatively benign and unreactive photochemically, whereas alkenes and oxygenated compounds are mostly absent from such emissions. Hence, airport stationary sources are unlikely to be an important source of the more toxic aviation-related HAPs compounds.

3.1.4 Ground Support Equipment

The ratio of aircraft to GSE VOC emissions varies enormously among airport emission inventories: from 1:1 for PHL to 24:1 for ATL (not shown above) (Unal, Hu et al. 2005). The average time that aircraft spend idling and the composition of the aircraft fleet and GSE fleet are all factors that contribute greatly to this ratio. The low GSE/APU emissions from BOS are likely attributable, at least in part, to Massachusetts Port Authority's (Massport's) Alternative Fuel Vehicle Program, which entails the conversion of vehicles to run on natural gas or electricity.

Even in cases where the reported VOC emissions from GSE are equal (in tons per year) to those from the aircraft, such as at PHL, FLL and ORD, the majority of the most toxic gas-phase HAPs compounds are emitted by the aircraft. This was shown in Figure 4 for PHL and more generally in Table 3 in which aircraft and GSE were assumed to emit equal amounts of VOC emissions by mass based on the emission inventories of PHL, FLL and ORD. This scenario represents the largest plausible contribution by GSE. That is, GSE emissions of VOCs are at most equal to aircraft emissions of VOCs, and at airports that have modernized the GSE fleet to alternative fuel (CNG, electricity) the GSE emissions of VOCs are substantially smaller than aircraft VOC emissions. Nevertheless, the relative toxicity-weighted emissions are largest for aircraft emissions, as shown in Figure 4. For smaller GSE VOC emissions (as reported by BOS (Vanasse Hangen Brustlin 2006) and ATL (Unal, Hu et al. 2005), all significant HAP emissions are dominated by the aircraft source.

3.1.5 Note on Fuel-Based Inventories

Currently it is difficult to assess the accuracy of GSE emissions as reported in emission inventories since fuel-based inventories are not available. A fuel-based inventory would list the total amount of gasoline, diesel, CNG, and jet fuel dispensed at the airport for use in GSE, aircraft, and stationary sources. Some environmental impact statements report some of this information (e.g., at ORD and PHL (URS 2003; KM Chng 2005); however, it is not clear if those reported numbers reflect the true amount of fuel consumed by GSE since outside contractors are usually hired to supply fuel. In principle, the use of fuel-based inventories is a very appealing approach to quantifying the emissions from GSE and stationary sources. Emission factors for GSE are currently expressed as grams of pollutant per brake-horsepower hour (see Section 5), and so calculation of total GSE emissions depends on knowledge of how much time each type of engine spends at a given workload. Fuel-based emission factors (i.e, grams of pollutant per kg of fuel) for gasoline and diesel engines have been extensively studied. Hence, reasonable calculations could be made regarding HAP emissions from GSE if accurate fuel inventories were available.

For example, at some airports aircraft and GSE are reported to emit comparable amounts of total VOCs. Consider a single

LTO cycle for a Boeing 737 with two CFM56-7B22 engines. Calculations using the ICAO certification values for time-in-mode and fuel flow rate (consisting of 26 min of idling at 7% thrust, which is not necessarily an accurate portrayal of the idle phase) indicate that the aircraft consumes 328 kg of jet fuel (115 gallons) during the idle/taxi phase, which is when the vast majority of HAP emissions occur (detailed later in Section 5, Figure 13). For the GSE emissions of HAPs per LTO to be comparable to the aircraft contribution, the GSE would either have to consume a comparable amount of fuel—if the HAP emission indices (in grams of pollutant per kg of fuel) are equal for aircraft and GSE—or much less fuel if the GSE fuel-based emission indices are higher than the aircraft emission indices. Without airport fuel inventories, this calculation is very difficult to execute. Of note is the estimate in the ORD environmental impact statement (FAA 2005, see Section 5.1.1.7) that the average fuel consumption by GSE vehicles "per aircraft operation" is 3.2 gallons. Such a calculation for the entire airport would need to reflect the entire fleet of aircraft and GSE vehicles in use, and the emission indices of VOCs (and therefore gas-phase HAPs) vary greatly among different aircraft engines and GSE vehicles.

SECTION 4

Health Effects of Aviation-Related Hazardous Air Pollutants

Several studies have assessed the public health risk posed by airport emissions. For example, the 2003 human health risk assessment for the Oakland International Airport (OAK) considered the incremental risk of increased emissions related to the proposed Airport Development Program on four exposure groups: airport workers, off-airport workers, residents, and school children (CDM 2003). The assessment concluded that the HAPs of greatest concern were diesel particulate matter, 1,3-butadiene, benzene, and acrolein. Aircraft particulate matter was not explicitly addressed. The toxicity of aircraft particulate matter is poorly understood (see *ACRP Report 6: Research Needs Associated with Particulate Emissions at Airports*).

A 2001 study of cancer rate statistics concluded that there was no general elevation of cancer incidence among populations living near ORD and Chicago Midway Airport (MDW). This study contained no explicit mention of individual HAPs, and stated that the available information was insufficient to evaluate cancer risk for a lifelong exposure to airport pollutants (Shen and Lehnherr 2001). A separate study concluded that the "hypothetical lifetime incremental cancer risks associated with concentrations measured at ORD's airport fence line are approximately five-fold higher than the cancer risks associated with 'background' air quality" (ENVIRON 2000), and that the chemicals that contribute the most to these risks (i.e., aldehydes, benzene, naphthalene) are detected in aircraft emissions.

4.1 Health Effects Associated with Aviation-Related Hazardous Air Pollutants

Chronic exposure[1] to many of the aviation-related HAPs has been associated with both cancer and noncancer effects. These health effects have been observed in controlled studies in laboratory animals, and in some cases for individuals exposed to these HAPs in occupational settings. Types of cancer associated with exposure to aviation-related HAPs are primarily lymphoreticular cancers (i.e., leukemia, lymphoma) and respiratory tract tumors. Types of noncancer effects associated with the aviation-related HAPs include alterations of the respiratory epithelium[2], neurological effects, developmental toxicity, and reproductive toxicity. For some of the HAPs, acute effects[3] such as irritation of the eyes and respiratory tract, exacerbation of asthma, as well as nausea and dizziness, may be a concern for shorter-term exposures to higher concentrations.

Among the HAPs reviewed, benzene and 1,3-butadiene are classified as human carcinogens by the EPA. This classification is based on increased incidence of leukemia in workers exposed to either benzene or 1,3-butadiene (USEPA 2002, 2003a). Several other HAPs are considered potential human carcinogens via the inhalation pathway, based on sufficient evidence of carcinogenic potential in animals, and limited or inadequate evidence in humans. These HAPs include acetaldehyde and formaldehyde, which cause nasal cell tumors in rats; and the polycyclic aromatic hydrocarbons (PAHs) benzo[a]pyrene (B[a]P), benzo[b]fluoranthene, and benzo[k]fluoranthene, which cause respiratory tract tumors in hamsters and mice (USEPA 1991a, 1991b, 1994a, 1994b, 1994c). In addition, in their draft Toxicological Review for naphthalene, EPA classified naphthalene as likely to be carcinogenic to humans via inhalation exposures, based on increased incidence of respiratory tract tumors in rats (USEPA 2004a). For the remaining HAPs, EPA has determined that there is inadequate evidence to characterize their carcinogenic potential in humans.

[1] Chronic exposure refers to repeated exposure to chemicals over the course of several years or longer.

[2] The epithelium consists of cells that line both the outside of the body (i.e., the skin) as well as internal spaces, such as the lung and the gastrointestinal tract.
[3] Acute effects occur immediately following exposure to a chemical, as opposed to chronic effects, which may occur after repeated, prolonged exposure to a chemical.

As noted above, noncancer health effects associated with chronic inhalation exposure to the airport-related HAPs reviewed include alterations of the respiratory epithelium, neurological effects, developmental toxicity, and reproductive toxicity. For example, effects on respiratory epithelium have been observed in rats exposed to acrolein (USEPA 2003b). Exposure to n-hexane is associated with peripheral neuropathy in both rats and humans (USEPA 2005a). Exposure to styrene and toluene has been associated with various neurological effects in humans, and exposure to xylenes is associated with neurological effects in rats (USEPA 1993, 2003c, 2005b). Both ethylbenzene and xylenes have been associated with developmental abnormalities[4] in laboratory animals (USEPA 1991c, 2003b). In addition, Silman et al. (1990) observed a clustering of scleroderma[5] associated with proximity to two different airports. The biological basis for this observation is not known, however.

Acute (<24 hr) and short-term (1–30 days) exposure to HAPs can also cause adverse health effects. For example, reactive compounds such as acrolein and formaldehyde can cause irritation of the eyes and respiratory tract; while volatile organic compounds, such as toluene and xylenes, can cause headaches, nausea, and dizziness (ATSDR 1999, 2000, 2005; USEPA, 2005c).

4.2 Evaluation of Chronic Health Effects for Aviation-Related Hazardous Air Pollutants

In order to evaluate both carcinogenic and noncarcinogenic aviation-related HAPs according to their potential to cause adverse health effects, RBCs for both cancer and noncancer endpoints were developed for this report, using toxicity criteria for the HAPs along with standard assumptions for evaluating exposure to carcinogens and noncarcinogens. These RBCs represent air concentrations that an individual could be exposed to for a prolonged period of time that would be associated with a negligible risk of developing cancer or other adverse health effects. Using RBCs allows a side-by-side evaluation of both carcinogenic and noncarcinogenic aviation-related HAPs in terms of their potential to cause adverse health effects.

4.2.1 Identification of Toxicity Criteria

Cancer due to inhalation exposure is characterized using an IUR, which represents the incremental upper-bound risk

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[4] Developmental abnormalities occur during growth and development of the embryo and fetus.
[5] Scleroderma involves abnormal growth of connective tissue supporting the skin and internal organs, which can cause hard, tight skin, and can also affect blood vessels and internal organs including the heart, lung, and kidneys (NIAMS 2006).

of an additional cancer per unit concentration (micrograms per cubic meter [$\mu g/m^3$]) in air (USEPA 1992). IURs are derived by extrapolating the concentration-response relationship modeled in the range of observed concentrations to lower concentrations associated with lower, more acceptable risk. Noncancer hazards due to inhalation exposure are characterized by a reference concentration (RfC), which is an air concentration, in milligrams per cubic meter [mg/m^3], at which no adverse biological effects are expected to occur, even in susceptible subpopulations (Barnes and Dourson 1988). RfCs are typically derived by identifying a lowest or no-observed-adverse-effect-level (LOAEL or NOAEL), which is then divided by uncertainty factors to account for inter- and intraspecies variability, as well as uncertainties relating to study design or database deficiencies. RfCs can also be developed using a benchmark concentration (BMC), which is a concentration associated with a specified change in response above background (typically 5% to 10%), based on the concentration-response relationship for all concentrations tested. With the BMC approach, uncertainty factors are applied to the lower 95% confidence limit on the BMC (BMCL).

Toxicity criteria listed on EPA's IRIS database were used for all HAPs, if available. Toxicity criteria on the IRIS database typically undergo an extensive evaluation and peer review process before being added to the database. If the IRIS toxicity criteria are up to date, they are generally considered to represent the best science available. If toxicity criteria were not available on the IRIS database, alternatives for toxicity criteria listed in California EPA's Office of Environmental Human Health Assessment (OEHHA) Toxicity Database; the Agency for Toxic Substances and Disease Registry (ATSDR); Health Canada; the Total Petroleum Hydrocarbon Criteria Working Group (TPHCWG), and the National Institute for Public Health and the Environment of the Netherlands (RIVM) were used, giving preference to values developed most recently and thus incorporating the most current evaluation of available scientific data. This analysis used IURs and chronic reference exposure levels (RELs) listed in the OEHHA database, chronic minimal risk levels (MRLs) developed by ATSDR, tolerable concentrations (TCs) developed by Health Canada, and RfCs developed by the TPHCWG. Chronic RELS, chronic MRLs and TCs are analogous to RfCs, both in their derivation (i.e., as a LOAEL/NOAEL or BMCL divided by uncertainty factors) and in their representation of a concentration that the general population, including sensitive subpopulations, can be exposed to with a negligible risk of experiencing adverse health effects (ATSDR 2007a; Health Canada 1996). Table 6 lists toxicity criteria used to evaluate chronic health effects for airport-related HAPs. For several of the HAPs which have undergone a review that is more current than that on the IRIS

Table 6. Summary of chronic toxicity criteria.

Criteria	Value	Source	Basis
Acetaldehyde			
IUR (μg/m^3)$^{-1}$	2.2×10^{-6}	USEPA 1991a (IRIS)	Nasal squamous cell carcinoma and adenocarcinoma in rats (Woutersen and Appleman 1984)
RfC (mg/m^3)	0.009	USEPA 1991a (IRIS)	Degeneration of olfactory epithelium in rats exposed for four weeks (Appleman et al. 1986, 1982)
TC (mg/m^3)	0.39	Health Canada 2000	Degeneration of olfactory epithelium in rats exposed for four weeks (Appleman et al. 1986, 1982)
Acetone			
Chronic MRL (mg/m^3)	3.1×10^{1}	ATSDR 1994	Neurological effects in humans (Stewart et al. 1975)
Acrolein			
RfC (mg/m^3)	2.0×10^{-5}	USEPA 2003c (IRIS)	Slight histopathological lesions in nasal cavity in 1/12 rats exposed (whole body) 6 hr/day, 5 days/week, 13 weeks at 0.4 ppm (Feron et al. 1978). In study by Cassee et al. (1996) disarrangement of respiratory/transitional epithelium was observed in 4/5 rats, and slight focal proliferative response observed in 3/5 rats exposed (nose only) to 0.25 ppm, 6 hrs/day for 3 days.
Benzene			
IUR (μg/m^3)$^{-1}$	7.8×10^{-6}	USEPA 2003a (IRIS)	Increased incidence of leukemia in pliofilm workers (Rinsky et al. 1981, 1987).
Chronic MRL (mg/m^3)	9.7×10^{-3}	ATSDR 2007b	Decreased lymphocyte count in humans (Lan et al. 2004).
1,3-Butadiene			
IUR (μg/m^3)$^{-1}$	3.0×10^{-5}	USEPA 2002 (IRIS)	Increased incidence of leukemia among male styrene-butadiene rubber production workers (Delzell et al. 1995).
RfC (mg/m^3)	2.0×10^{-3}	USEPA 2002 (IRIS)	Ovarian atrophy in mice (NTP 1993).
Ethylbenzene			
IUR (μg/m^3)$^{-1}$	2.5×10^{-6}	CalEPA, 2007	Increased incidence of renal tubule carcinomas and adenomas in male rats (NTP 1999).
RfC (mg/m^3)	1.0	USEPA 1991c (IRIS)	Skeletal variations, slightly reduced litter size, and elevated maternal liver, kidney and spleen weight (Andrew et al. 1981). Effects considered mild.
Formaldehyde			
IUR (μg/m^3)$^{-1}$	1.3×10^{-5}	USEPA 1991b	Nasal squamous cell carcinoma in rats. *Note: This is the value currently listed in EPA's IRIS database.*
	5.5×10^{-9}	USEPA 2005d	Nasal squamous cell carcinoma in rats; IUR for humans incorporates mechanistic/dosimetric information (CIIT 1999). *Note: This value is used by EPA in their National Air Toxics Assessment, and in the Emissions Standard for Plywood and Composite Wood Products.*
MRL (mg/m^3)	9.8×10^{-3}	ATSDR 1999	Mild damage to nasal epithelium (Holmstrom et al. 1989).
n-Hexane			
RfC (mg/m^3)	7.0×10^{-1}	USEPA 2005b (IRIS)	Peripheral neuropathy in rats (Huang et al. 1989).
Naphthalene			
IUR (μg/m^3)$^{-1}$	3.4×10^{-5}	CalEPA 2004a	Respiratory epithelial adenomas and olfactory epithelial neuroblastomas in male rats. *Note: This value is currently used by EPA for screening assessments.*
	1.0×10^{-4}	USEPA 2004a	Respiratory epithelial adenomas and olfactory epithelial neuroblastomas in male rats. *Note: This is a draft value currently undergoing review for inclusion in EPA's IRIS database.*
RfC (mg/m^3)	3.0×10^{-3}	USEPA 2004a	Nasal lesions in respiratory and olfactory epithelium in mice (NTP 1992).
Phenol			
Chronic REL (mg/m^3)	2.0×10^{-1}	CalEPA 2004b	Systemic effects including liver and nervous system effects in mice, rats and monkeys (Sandage, 1961; Dalin and Kristofferson 1974).

(continued on next page)

Table 6. (Continued).

Criteria	Value	Source	Basis
Polycyclic Aromatic Hydrocarbons			
IUR ($\mu g/m^3$)$^{-1}$	5.5E-05	USEPA 2001	Value represents 5% of the IUR for benzo[a]pyrene.
Propene			
Chronic REL (mg/m^3)	3.0	CalEPA, 2000	Inflammation and effects on epithelial cells of the nasal cavity in rats (Quest et al. 1984).
Styrene			
RfC (mg/m^3)	1.0	USEPA 1993 (IRIS)	Neuropsychological (CNS) effects in workers (Mutti et al. 1984).
Toluene			
RfC (mg/m^3)	5.0	USEPA 2005c (IRIS)	Neurological effects in workers (multiple studies).
Xylene			
RfC (mg/m^3)	1.0×10^{-1}	USEPA 2003b (IRIS)	Impaired motor coordination in male rats (Korsak et al. 1994).
Total Petroleum Hydrocarbons $C_{>8}$-C_{16} Aromatics *(1-methylnapthalene, 2-methylnaphthalene, dimethylnaphthalene)*			
RfC (mg/m^3)	2.0×10^{-1}	TPHCWG 1997	Reduced weight gain in rats (Douglas et al. 1993).
Total Petroleum Hydrocarbons C_5-C_8 Aliphatics *(n-pentane, n-heptane, 2,2,4-trimethylpentane)*			
RfC (mg/m^3)	1.8E+01	TPHCWG 1997	Increased liver weight, nephropathy, respiratory tract irritation, reduced body weight gain in offspring, liver tumors (various studies).
Total Petroleum Hydrocarbons C_9-C_{16} Aliphatics *(n-octane, n-nonane, n-decane, n-undecane, n-dodecane, C13-alkane, c14-alkane)*			
RfC (mg/m^3)	1.0	TPHCWG 1997	No significant adverse effects observed at highest concentration tested (Mattie et al. 1991).

Notes:
IUR   Inhalation unit risk
$\mu g/m^3$ Micrograms per cubic meter
mg/m^3 Milligrams per cubic meter
TC   Tolerable concentration
MRL   Minimal risk Level
RfC   Reference concentrations
RBC   Risk-based concentration

database, both the IRIS and the more current toxicity criteria are listed.

For formaldehyde we used an IUR of 5.5×10^{-9} per $\mu g/m^3$ (USEPA 2005d), based on an analysis by the Chemical Industry Institute of Toxicology (CIIT), as well as the formaldehyde IUR listed on EPA's IRIS database of 1.3×10^{-5} per $\mu g/m^3$ (USEPA 1991b).[6] Both values are based on increased incidence of nasal cavity squamous cell carcinoma in rats, as observed in a study by Kerns, Pavkov, and Donofrio et al. (1983). The CIIT value accounts for rat versus human differences in deposition of formaldehyde in the respiratory tract and formation of DNA-protein cross links, which are considered a critical lesion for nasal tumor formation. The CIIT value also accounts for the nonlinear dose-response for nasal cavity tumors as observed by Kerns et al. and others As discussed in a Health Canada priority substances list assessment report on formaldehyde (Health Canada 2001), induction of nasal tumors by formaldehyde likely occurs subsequent to cytotoxicity, which results in a sustained increase in nasal epithelial cell regeneration. The CIIT value has undergone peer review sponsored by EPA and Health Canada and is used by EPA in its National Air Toxics Assessment as well as in the Emissions Standard for Plywood and Composite Wood Products as representing the "best available peer-reviewed science at this time." (USEPA 2004b, 2005d). Nonetheless, we note that some scientists have expressed concerns regarding assumptions and choice of parameter values for the CIIT model. In addition, evidence from several epidemiology studies suggests that formaldehyde exposure may be associated with increased incidence of lymphohematopoietic malignancies, in addition to nasopharyngeal cancer. EPA is currently updating the IRIS file for formaldehyde, with an expected release date of July 2008, to consider the CIIT value in light of the concerns regarding model assumptions and parameter

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[6] The relative health impact, based on the risk-based concentration and the emission factor (discussed above in Section 2), was calculated using both IUR values. The rationale for including both values is to provide a sense of the magnitude of uncertainty associated with the cancer potency estimate for formaldehyde.

values, as well as the potential that formaldehyde may be a leukemogen.

For acetaldehyde we used Health Canada's TC for noncancer toxicity, as well as EPA's RfC for acetaldehyde.[7] At the request of Health Canada, the acetaldehyde TC has undergone independent peer review sponsored by Toxicology Excellence in Risk Assessment (TERA). Both the Health Canada TC and the IRIS RfC are based on degenerative changes in nasal epithelium as observed in a subchronic study in rats. The IRIS value, however, includes an uncertainty factor to account for use of a subchronic rather than a chronic exposure study that was not used by Health Canada. With respect to the subchronic-to-chronic uncertainty factor, the TERA peer review panel concluded this factor is not necessary as there is no indication that severity of the critical effect would increase with a longer study duration (TERA 1997). Moreover, effects on the respiratory epithelium of the structurally similar HAP formaldehyde are more closely related to exposure concentration than exposure duration (Health Canada 2001). The IRIS value also includes a full 10-fold interspecies variability factor, whereas a partial interspecies variability factor of 3 should be sufficient because EPA had converted the NOAEL from the rat study to a human equivalent concentration (HEC) NOAEL, which accounts for interspecies differences in toxicokinetics for respiratory tract toxicants.[8]

4.2.2 Toxicity Evaluation for HAPs Without Existing Criteria

Published toxicity criteria were not available for several of the airport-related HAPs, including the alkenes butene, ethene, and hexene; the aldehydes butanal, propanal (propionaldehyde), glyoxal and methylglyoxal, and the 2-alkenal crotonaldehyde. Here we present a semiquantitative assessment regarding their potential toxicity and impact relative to HAPs with established toxicity criteria. This assessment indicates that glyoxal, methylglyoxal, propanal (propionaldehyde), and crotonaldehyde may be important HAPs to consider, based on their potential toxicity and relative emissions.

4.2.2.1 Ethene

For ethene we identified a noncancer toxicity criterion from a two-year inhalation study in rats by Hamm, Guest, and Gent (1984), in which rats were exposed for 6 hr/day, 5 days/week, to ethene concentrations of 0, 300, 1,000 and 3,000 parts per million (ppm) (0, 345, 1,150, 3,450 mg/m³).[9] Rats were evaluated for clinical signs of toxicity including effects on liver, kidney, and blood, and tissues were evaluated for histopathological lesions. No effects were observed at the highest concentration (3,450 mg/m³), which is hence considered a NOAEL. If this concentration were adjusted to represent a continuous, exposure (24 hr/day, 7 days/week),[10] the resulting adjusted NOAEL would be 616 mg/m³. Accounting for uncertainty regarding inter- and intraspecies variability, as well as database deficiencies, an acceptable exposure level in humans could be anywhere from 300- to 1,000-fold lower, or approximately 0.6-2.0 mg/m³. Considering potential noncancer toxicity of ethene relative to emissions, it does not appear that ethene would pose a substantial health concern relative to the prioritized HAPs identified in Table 1.

There is also some concern that exposure to high levels of ethene may be associated with an increased risk of cancer. This concern stems from the *in vivo* metabolism of ethene to ethylene oxide (EtO), which has been classified as a human carcinogen by the International Agency for Research on Cancer (IARC 1994). There is uncertainty regarding the shape of the dose-response for EtO-induced tumors at low exposure concentrations, however, and hence, uncertainty whether exposure to any level of ethene would produce sufficient levels of EtO, due to saturation of the metabolic pathway that converts ethene to EtO. In addition, while EtO is mutagenic, there is no evidence that ethene is mutagenic (Rusyn, Shoji, et al. 2005). Nonetheless, several researchers have suggested that the lack of an increase in tumors in ethene-exposed laboratory animals may be due to the lack of sensitivity of typical carcinogenicity bioassays to detect very small, but potentially biologically significant increases in tumor incidence (Tornqvist 1994; Walker, Yuh, et al. 2000).

To address the potential that exposure to ethene may be associated with an increased risk of cancer, we considered results from an epidemiological study by Steenland, Stayner, and Deddens (2004), who observed a positive exposure response trend for lymphoid tumors among workers exposed to ethylene oxide. There was no increase in tumor incidence for workers in the lowest exposure group (> 1199 ppm-days).

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[7] While we believe the Health Canada TC value represents the most current scientific understanding of acetaldehyde's noncancer toxicity for the purposes of establishing a prioritized research agenda, any quantitative health risk assessment of airport exposures should rely on the most appropriate toxicity value for the specific purposes of the risk assessment.

[8] The full interspecies uncertainty factor of 10 includes partial uncertainty factors of 3 each to account for interspecies differences in toxicokinetics (i.e., absorption, distribution, metabolism, and elimination) and toxicodynamics (i.e., interaction of chemicals with target sites in the body and subsequent reactions causing adverse health effects). A partial uncertainty factor of 3 can be used if either toxicokinetics or toxicodynamics are expected to be similar between laboratory animals and humans, or if the RfC is based on a human equivalent concentration that accounts for differences in toxicokinetics.

[9] Based on a molecular weight for ethene of 28.0536, according to the following conversion formula:

$$mg/m^3 = ppm \times \frac{MW}{24.45}$$

[10] $3450\ mg/m^3 \times \left(\frac{5\ days}{7\ days}\right) \times \left(\frac{6\ hours}{24\ hours}\right) = 616 mg/m^3$

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Assuming a standard 25-year occupational exposure duration, at 250 days/year (USEPA 2004c), this exposure level would correspond to an average daily exposure of approximately 0.2 ppm EtO. Accounting for uncertainty regarding susceptibility of potentially sensitive subpopulations, as well as relative potency of EtO and ethene as assessed by Walker, Yuh et al. (2000),[11] a comparable ethene concentration for the general population could be on the order of 1 ppm, or approximately 1 mg/m³.[12] As with potential noncancer toxicity of ethene, it does not appear that potential carcinogenicity of ethene relative to emissions would be greater than that for other carcinogenic HAPs.

4.2.2.2 Glyoxal and Methylglyoxal

Glyoxal and methylglyoxal are mutagenic aldehydes with two carbonyl groups (IARC 1991; NEG 1995). There are no toxicity studies available for deriving toxicity criteria for these two compounds, but the available data suggest they could be carcinogenic. For example, in addition to being mutagenic, glyoxal significantly increased the incidence of stomach tumors in rats pretreated with an N-methyl-N′-nitro-N-nitrosoguanidine (MNNG), which is both mutagenic and carcinogenic (NEG 1995). In an *in vitro* study, levels of DNA adducts at equivalent molar concentrations were approximately 20-fold higher for methylglyoxal as compared with acetaldehyde (Vaca, Nilsson et al. 1998). Considering that these two aldehydes may be at least as potent as acetaldehyde, and are emitted in fairly large quantities, they may represent a health concern that is comparable if not greater than that for the prioritized HAPs identified in Table 1.

4.2.2.3 1-Hexene

We identified a toxicity criterion for 1-hexene based on a 13-week inhalation study in rats by Gingell, Bennick, and Malley (1999). Rats were exposed to hexene for 6 hr/day, 5 days/week to concentrations of 0, 300, 1,000, and 3,000 ppm (0, 1,033, 3,443 and 10,330 mg/m³) and evaluated for clinical signs of toxicity including effects on liver, kidney, and blood, and tissues were evaluated for histopathological signs of toxicity. The NOAEL from this study was 3,443 mg/m³, based on decreased weight gain in female rats and slight organ weight changes in both male and female rats at 10,330 mg/m³. This NOAEL was adjusted as above for ethene yielding an adjusted NOAEL of 615 mg/m³.[13] Accounting for uncertainty related to inter- and intraspecies variability, database deficiencies, as well as use of a subchronic rather than a chronic study, an acceptable exposure concentration could be as much as 1000-fold lower than this value, or approximately 0.6 mg/m³. As with ethene, it does not appear that hexene would be a greater health concern than the HAPs identified in Table 1.

4.2.2.4 Toxicity Criteria Based on Surrogate Compounds

For several airport-related HAPs without existing toxicity criteria we considered toxicity of surrogate compounds in the same class of compounds, assuming that toxicity would be comparable based on structural similarity. These HAPs included the aldehydes propanal (propionaldehyde) and butanal, for which we used acetaldehyde as a surrogate; the alkene 1-butene for which we used propene as a surrogate; and the 2-alkenal crotonaldehyde for which we used acrolein as a surrogate. Compounds were selected as surrogates based on having similar functional groups (i.e., an aldehyde, a carbon-carbon double bond, or both) and similar molecular weight. For all of these HAPs, we used surrogate compounds with lower molecular weight. Because toxicity tends to decrease with increasing molecular weight within a given class of compounds (Segovia, Crovetto et al. 2002), use of toxicity criteria for these surrogate compounds should be health-protective. Table 7 shows the chemical structures for these HAPs and their corresponding surrogate compounds. Assuming comparable toxicity for these HAPs and their corresponding surrogate compounds, both propanal (propionaldehyde) and crotonaldehyde may be important HAPs to consider in terms of their potential health concern.
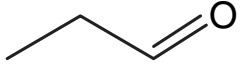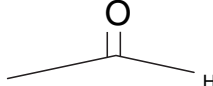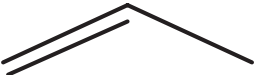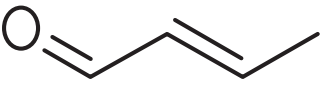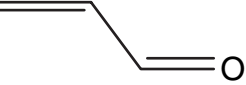
Note that EPA Region 9 lists a preliminary remediation goal for crotonaldehyde of 3.5×10^{-3} µg/m³, based on an unpublished oral cancer slope factor.[14] Considering that crotonaldehyde is likely to be reactive, health effects associated with exposure to crotonaldehyde are expected to be localized to the route of exposure (i.e., respiratory system for inhalation exposures, gastrointestinal tract for oral exposures) rather than systemic. As such, it would not be appropriate to evaluate inhalation exposures using an oral toxicity criterion. In any case, the toxicity criterion used in this analysis provides a more conservative (i.e., more potent) estimate of toxicity for crotonaldehyde.

4.3 Calculation of Risk-Based Concentrations for Chronic Health Effects

Risk-based concentrations (RBCs) for cancer and noncancer health effects were calculated as follows:

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[11] According to Walker, Yuh, et al. (2000), an EtO concentration of 1 ppm corresponds with an ethene concentration of approximately 40 ppm.

[12] $1\,ppm \times \dfrac{28.0536(MW)}{24.45} = 1mg/m^3$

[13] $3443\,mg/m^3 \times \left(\dfrac{5\,days}{7\,days}\right) \times \left(\dfrac{6\,hours}{24\,hours}\right) = 615\,mg/m^3$

[14] The Region 9 PRG Table lists U.S. Environmental Protection Agency's Health Effects Assessment Summary Tables (HEAST) as the source for the oral CSR. However, the most recent (1997) HEAST Tables do not provide any toxicity information for crotonaldehyde.

Table 7. Chemical structures for propanal (propionaldehyde), butanal, butene, crotonaldehyde, and their corresponding surrogate compounds.

HAP without Toxicity Criteria	Surrogate Compound
Propanal (Propionaldehyde)	Acetaldehyde
Butanal	
Butene	Propene
Crotonaldehyde	Acrolein

$$RBC_{cancer}\,(\mu g/m^3) = \frac{CR}{IUR} \times \frac{AT_{cancer}}{EF \times ED}$$

$$RBC_{noncancer}\,(\mu g/m^3) = 100 \times HQ \times RfC \times \frac{AT_{noncancer}}{EF \times ED}$$

Where:

AT_{cancer} = Averaging time – cancer (25550 days);
$AT_{noncancer}$ = Averaging time – noncancer (10950 days);
CR = Acceptable cancer risk (1×10^{-6});
ED = Exposure duration (30 years);
EF = Exposure frequency (350 days/year);
HQ = Hazard quotient (1);
IUR = Inhalation unit risk (risk per $\mu g/m^3$ – chemical specific); and
RfC = Reference concentration (mg/m^3 – chemical specific).

We used standard assumptions for averaging time, exposure duration, and exposure frequency, as recommended by EPA (USEPA 1989).

Table 3 listed RBCs along with relative emissions factors for airport-related HAPs.

4.4 Evaluation of Acute Exposures for Aviation-Related HAPs

For evaluating acute effects the report researchers identified acute exposure guidelines (AEGLs), acute minimal risk levels (MRLs), and acute inhalation reference exposure levels (RELs). AEGLs are developed through a federal advisory committee with input from stakeholders for use in chemical emergency planning, prevention and response programs, and include peer review by the National Research Council (USEPA 2007). AEGLs are established at three levels, with increasing severity, for exposure periods ranging from 10 min to 8 hr. For this analysis we selected AEGL-1 values, which correspond with concentrations at which the general population, including susceptible subpopulations, might experience transient and reversible discomfort or irritation, but not any disabling effects (NRC 2007). Acute MRLs are developed by ATSDR, and represent a concentration that would not be associated with adverse health effects including in sensitive individuals (i.e., a "no-effect" concentration), for an exposure period of 1–14 days. Acute RELs are developed by California Environmental Protection Agency's Office of Environmental Health Hazard Assessment. As with the acute MRLs, the acute RELs represent a "no-effect" concentration at which no adverse health effects are expected, including for the most sensitive individuals in an exposed population (CalEPA 1999). Acute RELs are applicable to a 1-hr exposure period unless they are based on reproductive or developmental endpoint, in which case they are applicable to an exposure period of several hours. Toxicity criteria for evaluating acute exposures are presented in Table 8.

As noted in Section 2, toluene and xylene are emitted in fairly large quantities, yet what is currently known regarding their toxicity indicates they are much less of a health concern than that of the prioritized HAPs identified in this analysis. As indicated by the values in Table 8, this is true for both chronic and acute toxicity. The determination that toluene and xylene airport emissions likely do not present a substantial health concern is supported by an evaluation of acute human health risks for Oakland International Airport (CDM 2003). This evaluation indicates that CalEPA's acute RELs for toluene and xylene are more than 2,000-fold greater than estimated air concentrations, which provides a very wide margin of safety to account for any uncertainties in estimates of toxicity or exposure.

Table 8. Acute toxicity criteria for airport-related hazardous air pollutants.

HAP	Toxicity Criterion (ppm)			
	REL[a] 1–6 Hours	AEGL-1 1 Hour	AEGL-1 8 Hour	MRL 1–14 Days
Acetaldehyde		45	45	
Acetone		200	200	26
Acrolein	0.00008	0.03	0.03	0.003
Benzene	0.4	52	9	0.009
1,3-butadiene		45	45	
Formaldehyde	0.08	0.9	0.9	0.04
Methanol		530	270	
Phenol	1.5	15	6.3	0.02
Propane		5,500	5,500	
Styrene	5	20	20	
Toluene	10	200	200	1
Xylenes	5	130	130	2

Data Sources: ATSDR 2007a (MRLs); CalEPA 1999 (RELs); USEPA 2007 (AEGLs).

Notes:
ppm parts per million
HAP hazardous air pollutant
REL reference exposure level
AEGL acute exposure guideline
MRL minimum risk level

[a]   Benzene REL is for a 6-hr exposure period, all other RELs are for a 1-hr exposure period.

SECTION 5

Emission Factors and Activity Factors

Emissions data are used in conjunction with dispersion/chemistry models in order to predict actual concentrations in particular locations. Emissions from most pollution sources are expressed or calculated as the product of two separate components: emission factors and activity factors. For example, the emission factors for on-road mobile sources are commonly tabulated as grams per vehicle mile. By combining this emission factor with an activity factor, in this example, miles traveled, the total emission can be estimated. For aircraft emissions, emission factors are fuel-based, e.g., g of CO/kg of fuel (also known as an emission index). Off-road emission factors are expressed differently, as g/BHP-hr (grams per brake-horsepower hour).

Below is a description of the status of knowledge and uncertainties associated with the emissions produced from the following sources: aircraft, airport operations, ground-access vehicles, stationary sources, and de-icing.

5.1 Aircraft

This category includes emissions from gas turbine engines, turboprop engines, internal combustion piston engines for fixed-wing aircraft, helicopters, and nonrigid airships such as blimps. As total fuel consumption at most airports is dominated by commercial aircraft activity, the emphasis of this report is on high-bypass turbo-fan equipped commercial jets; however, piston-engine aircraft emissions will also be discussed.

5.1.1 Commercial Aircraft Emission Factors

The ICAO has an established testing protocol for new jet engines. The results of this certification process are tabulated in the ICAO databank (www.caa.co.uk). The mass emissions of NO_x, CO, and unburned hydrocarbons (UHC) are compiled in units of mass per kilogram of fuel for each

jet engine at four defined operational points. ICAO defines these operational points as the fraction of rated thrust from the engine for the following named conditions: idle (7%), approach (30%), climb-out (85%), and take-off (100%). The ICAO databank also tabulates the result of a measurement of exhaust opacity known as the smoke-number, however, reporting only the maximum smoke number is mandated. Smoke-number is frequently omitted for other operational conditions. All tabulated values have been either conducted at standard atmospheric pressure, temperature, and relative humidity or corrected to this reference state. The fuel flow at each power setting is also tabulated in this databank. For the ICAO species, this database serves as the primary source of aviation emissions factor information. Volatile organic compounds (VOCs) (UHCs) exhibit a different emission profile than does NO_x. Figure 6 depicts the average NO_x and CO emission indices versus throttle setting.

The emission indices of CO are greatest at low throttle and decrease dramatically with increasing power settings. NO_x EIs start at an average value of ~5 g/kg at low thrust and unlike for CO, the EI increases with increasing throttle. This depiction is not quantitatively representative of any single specific engine, but is qualitatively true for all jet engines in the sense that CO is relatively high at low engine power and NOx is relatively high at high engine power. The UHC trend is qualitatively similar to the trend observed in CO emissions. Unburned hydrocarbons and VOCs are mostly synonymous in this context.

Emissions of VOCs exhibit a similar trend with engine power as CO emissions do. This is depicted in Figure 7, in which an average VOC emission factor and fuel flow is depicted versus the throttle setting. Consideration of the emission factors, fuel flow rates, and times spent in mode indicate that the activity leading to the greatest gas-phase HAP emissions (excluding particulate bound PAH species) is idling.
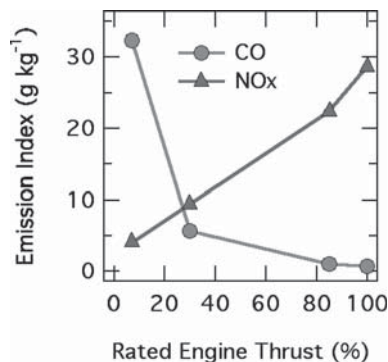
Figure 6. Average NO$_x$ and CO emission indices versus throttle setting.
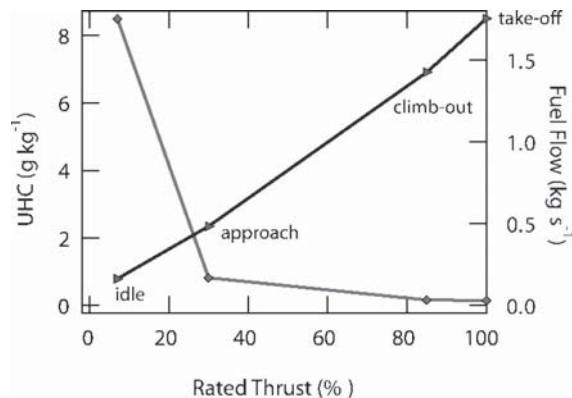

Figure 7. Generalized depiction of UHC emission index and fuel flow rate versus engine power.

One of the more definitive speciated measurements of hydrocarbons in jet exhaust is the work of Spicer, Holdren et al. (1994). This work reported on a wide variety of individual hydrocarbons in the exhaust of a TF-39 and a CFM56 engine (similar to those found on Boeing 737 airframes) fueled by JP-5 fuel. Whole air canister samples were collected for off-line analysis by various gas-chromatographic (GC) techniques while the engine was running at ground idle and at 30% and 80% of rated thrust. The work of Spicer was the most authoritative manuscript on this topic for over a decade. Additional work was performed in the late 1990s by Gerstle and co-workers on behalf of the U.S. Air Force, though these measurements focused on military engines (Gerstle, Virag et al. 1999). Slemr et al. reported hydrocarbon emission factors from a Rolls Royce M45H-Mk501 engine measured during flight (Slemr, Giehl et al. 2001).

In the last few years, several emission measurement campaigns have significantly contributed to the total knowledge base of VOC emissions from commercial aircraft. Table 9 summarizes the aircraft engines characterized during these campaigns.

For all of the engines presented in Table 9, the particulate and gas-phase components of the engine exhaust were analyzed by a team of research groups. VOCs were measured by either in-situ instruments (e.g., proton transfer mass spectrometry [PTRMS], tunable infrared laser diode absorption spectrometry [TILDAS]) or whole air canister samples for subsequent analysis by GC-MS. Additional studies at the Delta/Atlanta Hartsfield and JETS-APEX2 studies focused on the measurement of advected exhaust plumes from in-use aircraft. Such measurements are analogous to on-road remote sensing measurements in that emission factor distributions can be measured.

VOC measurements during these campaigns have both confirmed past results and revealed new findings. The main findings are summarized below.

Table 9. Summary of recent aircraft engine exhaust measurement campaigns.

| Engine	Airframe	Campaign
RB211-535E4	B757	EXCAVATE
CFM56-2C2	DC-8	APEX
CFM56-3B1	B737	JETS-APEX2, APEX3
CFM56-7B22	B737	JETS-APEX2
RB211-535E4-B	B757	APEX3
RB211-535E4-B phase 5	B757	APEX3
PW4158	A300	APEX3
AE3007-A	Embraer	APEX3
AE3007-A1E	Embraer	APEX3
CJ6108A	NASA Lear Jet	APEX3
Notes: EXCAVATE: EXperiment to Characterize Aircraft Volatile Aerosol and Trace-Species Emissions, NASA-Langley, 2002. APEX: Aircraft Particle Emissions eXperiment, Dryden Air Force Base, 2004. JETS – APEX2: Oakland International Airport, 2005. APEX3: Cleveland International Airport/NASA-Glenn, 2005.		

5.1.1.1 VOC Emission Factors versus Thrust

As observed by Spicer and colleagues (1994), VOC measurements are a strong function of engine power and are highest at low thrust; decreasing dramatically at higher powers. Figure 8 shows the formaldehyde (HCHO) emission ratio as a function of fuel flow rate (power) for the CFM56-2C1 engine studied during APEX (Yelvington, Herndon et al. 2007). The HCHO emission ratio (parts per billion [ppb] of HCHO per ppm of carbon dioxide [CO_2]) is proportional to a fuel-based emission index (g HCHO per kg of fuel). The emission ratio decreases by two orders of magnitude between low thrust (idle) and high thrust (take-off) settings. Furthermore, the decrease in HCHO emission index between 4% rated thrust and 7% is more than a factor of three. The ICAO certification power setting for idle is 7% rated thrust, though lower thrust levels (e.g., 4%) appear to more accurately reflect true operational ground idle.

5.1.1.2 VOC Emissions Follow a Universal Scaling Law

The ratio of any two VOCs in engine exhaust is approximately constant and independent of engine, power setting, fuel content, and ambient temperature. Figure 9 displays this feature. Data from one CFM56-3B1, two RB211-535E4-Bs, and one PW4158 as measured at APEX3 were used in this plot. The ratio of the emission index of any chosen VOC to that of formaldehyde is a constant, as indicated by the linear fits through each group of points. Thus speciation profiles that have relied on the work of Spicer, Holdren et al. (1994) are likely fairly accurate. Formaldehyde is a somewhat arbitrary choice for the x-axis, though was measured with
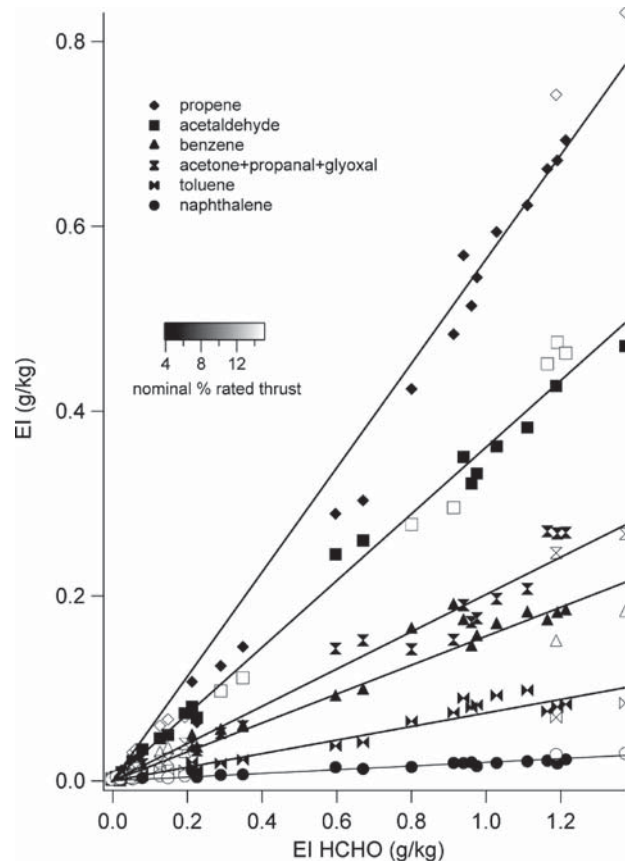
Credit: Knighton, Herndon et al. 2006. Used with permission.

Figure 9. Ratios of several VOCs to HCHO.

separate instrumentation (TILDAS) than the other VOCs (PTRMS). Thus the variation in formaldehyde emission index with power and temperature described elsewhere in this section hold true for all VOC species measured. It is unknown whether this universal scaling is affected by extremely low temperatures or engine age/maintenance.

5.1.1.3 VOC Emission Factors Are Highly Dependent on Ambient Temperature

Volatile organic compound emissions increase greatly with decreasing temperature. The variation of HCHO emission index with temperature is evident in Figure 8. Figure 10 depicts the measured temperature dependence of HCHO emissions from the APEX-1 campaign. For comparison, the Boeing Fuel Flow Method 2 (BFFM2) temperature dependence has been added to the data (Baughcum, Tritz et al. 1996), depicted as the solid lines. These lines have been computed by scaling the measured emission rate at 25°C by the ratio of the temperature dependent function to that at 25°C using the following equation:

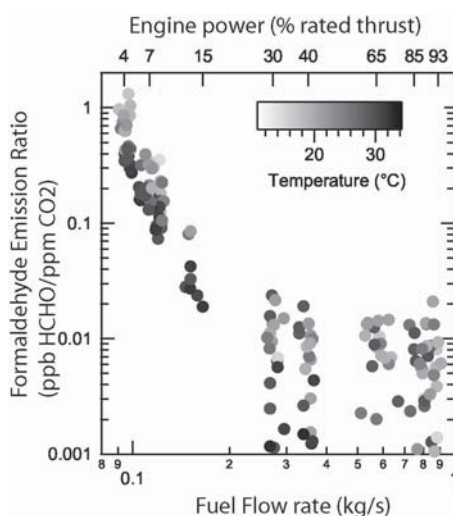$$\text{Emission Rate} = \text{BFFM2(T)}/\text{BFFM2(25 C)} * \text{Measured HCHO ER.}$$

Figure 8. Formaldehyde (HCHO) emission ratio as a function of engine power.
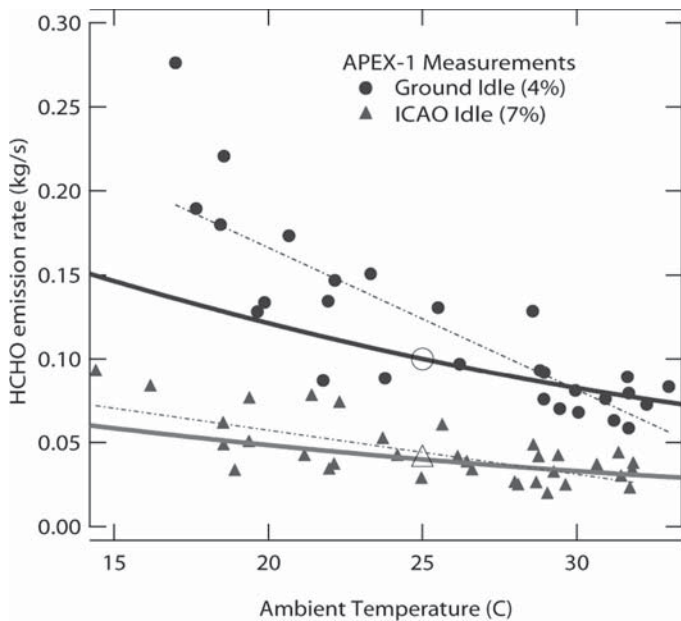
Figure 10. APEX-1 measured temperature dependence of formaldehyde (HCHO) emissions.

In this way, only the temperature dependence of the BFFM2 modeling function is compared to the data. An absolute comparison is not directly possible, as the procedure was developed to scale reference ICAO UHC.

Though the absolute magnitude of the reference value may be arbitrary, the temperature dependence is evidently slightly steeper than predicted. It should be noted that the developers of the BFFM2 protocol have more certainty in its ability to predict NO_x emission at take-off and during cruise aloft. In the description of the method, it acknowledges challenges associated with using 30% and 7% as the only model inputs for CO and HC emissions.

There are no measurements below 15°C as such knowledge of HAP emissions in cold temperatures is extremely limited.

5.1.1.4 Negligible Variation of VOC Emission Factors with Fuel Composition

Variations in aromatic content and sulfur content were found to have a minimal effect on VOC emissions during APEX and are minor compared to variation with engine power and ambient temperature (Anderson, Chen et al. 2006; Knighton, Rogers et al. 2007; Yelvington, Herndon et al. 2007). Note that while the "aromatic" content of the fuels tested varied from 18% to 22%, the C/H ratio was not affected. Clearly the full variation in hydrocarbon matrix of the fuel was not fully explored.

5.1.1.5 Agreement Between GC-FID and Individually Measured VOCs

At APEX, the sum of individual VOC measurements and a total HC measurement by GC-FID (flame ionization detec-

tor) agreed to within 10% at low powers. At low power (<10% thrust), the sum of compounds measured by TILDAS and PTR-MS was ~10% higher than the GC-FID measurement, quite possibly due to the latter technique's lack of sensitivity to formaldehyde. At higher powers, the total VOC concentrations were lower than the detection limit for the TILDAS and PTR-MS as deployed during those campaigns (Yelvington, Herndon et al. 2007).

5.1.1.6 Absolute VOC EIs Vary by More Than a Factor of 10 Between Different Engines

This is reflected in both the individually-measured VOC emission indices as well as the ICAO certification data for total hydrocarbon (HC) emissions. Table 10 displays the HCHO emission index (EI_{HCHO}) of the engines observed at the APEX campaigns and the corresponding ICAO certification HC emission index, both at 7% power (ICAO idle). The CF6 engine is included in the table for comparison.

The variation in the $HC_{ICAO}/HCHO_{APEXx}$ ratio illustrates the difficulty in comparing these quantities due to the large variation in VOC emissions with power and temperature. The variations should not be interpreted as actual variations in the HCHO contribution to total HC. Comparison of individual VOC measurements to the total HC measurement by GC-FID has not been done for JETS-APEX2 and APEX3 yet.

5.1.1.7 Emission Factors: True Idle versus 7% (ICAO)

The category labeled "idle" in the ICAO databank of emissions is a standardized thrust setting. The certification setting (7% of rated maximum engine thrust) is somewhat greater than the setting at which many modern high-bypass ratio engines actually idle in today's fleet. Although it is not formally correct, numerous data plots and representations attribute "true ground idle" to be approximately 4% of rated thrust. Figure 10 portrays the temperature dependence of actual HCHO emissions measured during APEX1 along with the predicted temperature dependence of Boeing Fuel Flow Method-2. This figure also shows the increase in HCHO emission rate between 7% and 4% (ground-idle).

A current problem in emission inventory modeling (such as EDMS) involves the treatment of how the taxi phase of the LTO is treated. This discussion is tightly coupled to the difference in VOC emission rates between 7% and ground-idle. In each of the studies where the engine has been measured at both 7% and "ground idle," the CO and VOC species are consistently greater at the lower effective thrust setting. Though the number of aircraft engines sampled through the EXCAVATE and APEX missions has grown, a systematic characterization of emissions resulting from the range of idle levels used (3% to 10%) is not available.

Table 10. Comparison of formaldehyde and ICAO HC emission indices for several engines.

Engine	EI_{HCHO} (7%, g/kg)	ICAO EI_{HC} (g/kg)	HC $_{ICAO}$/HCHO$_{(APEXx)}$
CFM56-2C1	0.43	NA	NA
CFM56-3B1	0.33	2.3	7.0
CFM56-7B22	0.31	2.5	8.1
RB211-535E4B	0.05	0.14	2.8
RB211-535E4-B phase 5	0.22	0.28	1.3
PW4158	1.00	1.8	1.8
AE3007-A	0.41	2.5	6.1
AE3007-A1E	0.54	3.5	6.5
CF6-6D	NA	21	NA

Notes:
EI_{HCHO} formaldehyde emission index
g/kg   grams per kilogram
ICAO   International Civil Aviation Organization
EI_{HC} hydrocarbon emission index
APEX   Aircraft Particle Emissions eXperiment
NA   not applicable

Measurements of in-use aircraft at Oakland Airport during JETs-APEX2 have helped to characterize the real-world emissions at true operational idle. Although use of 7% thrust was known to be too high by aircraft operators, the use of 7% idle in engine calculations has remained common in numerous studies (e.g., Pison and Menut 2004; Unal, Hu et al. 2005).

Figure 11 depicts the underestimate of 1,3-butadiene emissions from PHL resulting from the assumption of 7% for the thrust value used during the idle phase. The shaded area outside of the circle represents the conservative underestimated amount, assuming a temperature of 18°C.
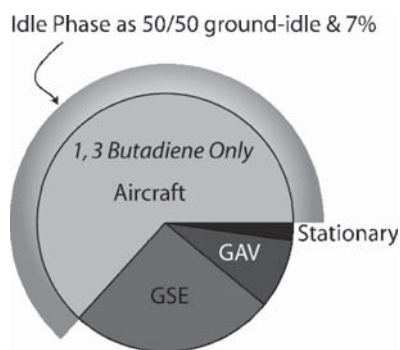
Figure 11. Depiction of the emissions of 1,3-butadiene from aircraft, GSE, GAV, and stationary sources at PHL. The shaded area outside of the circle represents the extra emissions from aircraft when calculated assuming that the power settings used during idle/taxi are equal amounts of time spent at 7% thrust and 4% thrust (versus the standard 7% assumption).

5.1.1.8 Reactive Aldehyde Emission Factors

Due to the importance that this report and others assign to acrolein as an air toxic, a few details regarding its emission indices are included here. The emissions of acrolein from aircraft engines are greater than anticipated by simple extrapolations of other combustion sources. The ratio of acrolein to formaldehyde (HCHO) in gasoline "engine out" (pre-catalytic converter) is 0.4% by mass (Schauer, Kleeman et al. 2002). This same ratio in diesel truck exhaust is slightly greater, 15% by mass (Schauer, Kleeman et al. 1999). In the Spicer, Holdren et al. (1994) determination of VOC content in the exhaust of the CFM-56, the measured ratio of acrolein to HCHO is 29%, by mass.

Preliminary analysis of wind-advected plumes at the taxiway of Oakland International Airport using the fast response online instrumentation during the JETS/APEX2 campaign supports the observations of elevated acrolein emissions from aircraft engine. One such event is depicted in Figure 12, where the exhaust from an in-use CF-6 engine was sampled. The time series show high correlation between the sum of the butene isomers and acrolein, HCHO, and CO_2. The PTR-MS instrument used to measure acrolein + butene was not using a recently developed scrubber system which can distinguish the two compounds independently. As a result, this analysis must rely on the Spicer et al. fraction of acrolein to total acrolein + butene isomers (0.64). The Spicer, Holdren et al. fraction is very similar to that observed in diesel truck exhaust (Schauer, Kleeman et al. 1999). The advected plume data in Figure 12 suggest the ratio of acrolein to HCHO is 56%. This further underscores

Figure 12. Acrolein sampled from CF-6 engine exhaust.

the need to characterize the acrolein emission index with robust measurements.

5.1.1.9 Aircraft Emissions at Engine Start

At many airports, aircraft can plug-in to an electrical service at the gate, which provides basic power to the aircraft during preparation for flight and deplaning, and allows the APU to be turned off. At other airports the APU is used to generate power for th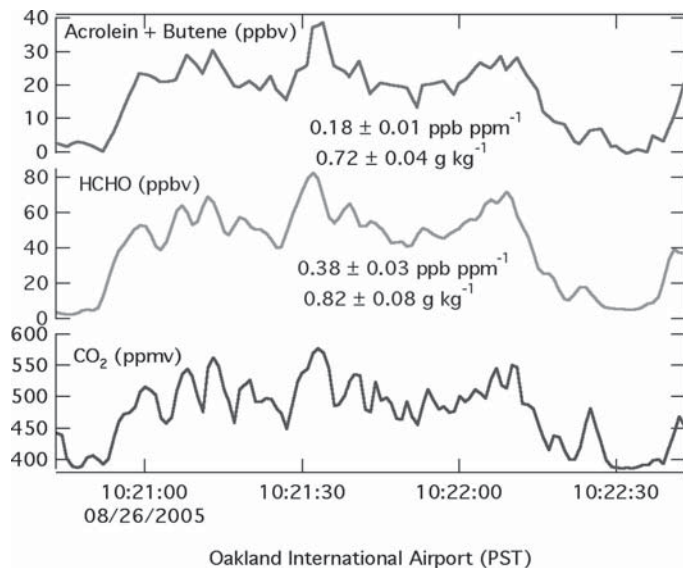e aircraft while at the gate and, in either case, the APU is used to start the main engines. In starting the engine, the turbo-machinery is first accelerated to a nominal starting rotational speed, at which point, fuel is supplied to the combustor and a fuel spray is generated. With the initiation of the fuel flow, the spark ignition system is activated, and a flame is quickly established in the combustor. Once the flame is established, the rotation speed and the fuel flow are increased together to the nominal ground idle operating point. Over the course of 30 to 90 sec, the temperature of the engine reaches a stable condition and the emission indices of hydrocarbons and CO stabilize.

As it pertains to total emissions accounting, any fuel that is pushed through the combustor before ignition is "unburned." The nature of these emissions will have the same speciation as evaporative emissions from the fuel stock. This pre-ignition contribution will have a very different speciation profile than the engine-on profile of HAP emissions, and they are much less toxic, since they consist mainly of alkanes.

There are a few different approaches to assessing the magnitude of start-up emissions relative to the total emissions during an LTO. Direct determinations, based on fuel flow measurements and analytical UHC instruments, are challenging because the unburned fuel can foul sampling lines, and standard methods using combustion reference gases cannot be used prior to the initiation of the flame in the combustor. Alternately, the combustion efficiency can be estimated from engine exit plane temperature measurements. If assumptions about the HC profile are associated with combustion efficiency, the start-up emissions can be estimated.

Such calculations using unpublished test data yield estimates that pre-ignition emissions of unburned fuel are between 30 and 90 g of fuel (hydrocarbons). The range is largely a result of the uncertainty in the ignition timing. The composition of this emission source should resemble evaporated fuel and be less similar to the exhaust HC profile. Pre-ignition emissions are estimated in Table 11. This estimate uses a fuel flow rate (kg/s) that is half of the ICAO 7% value for a CFM56-7B22 engine during the initial act of starting the engine.

The next line involves estimating the emissions at the critical point of ignition. The contribution of the near-ignition phase is small compared to the total LTO; however, there is

Table 11. Single engine emissions of hazardous air pollutants at start-up.

Condition	Emission Index (g kg⁻¹)	Time	Fuel Flow (kg s⁻¹)	Emission UHC (g)	Emission ~HAP (g)
Pre-ignition	1000	0.3-0.5 s	0.05	15-25	-
Ignition	1000-10	0.01-10 ms			<1
Warm-Up	3 – 6	30 – 90 s	0.105	10 – 50	10 – 50
Taxiway Activity	2.5	24 min	0.105	410	410

Pre-ignition—The time and fuel flow values have been estimated using an unpublished draft of a working paper on start-up emissions (Will Dodds, GE, personal communication).

Ignition—These large ranges are meant to indicate the vast uncertainty in this transition state in the combustor.

Warm-up—The approximate "doubling" of the emission index during warm-up as well as the estimate of how long the machinery of the engine requires to come to a stable temperature is based on an unpublished analysis of an RB211-535-E4-B engine during APEX3.

Taxiway activity—As the template for these estimates, the emission index and fuel flow rate for a CFM56-7B22 have been drawn from the engine certification value.

no certainty as to the compositional make up of these emissions. There is no known measurement of in-use engine emissions at the point of ignition, however these estimates indicate it will be small relative to the emissions during an LTO.

An unpublished analysis of an engine test from APEX3 indicates that the emissions stabilize about 40 sec after start. Other anecdotal material suggests this is a reasonable estimate of a typical warm-up time. Preliminary analysis of APEX3 data indicates that the initial magnitude of the HC emission indices was approximately twice as high as idle emission indices. For example, the initial CO emission index was measured to be 70 g kg^{-1} and this settled to just less than 35 g kg^{-1} after warm up. The direct measurements of formaldehyde and benzene saw very similar trends.

The total impact of the warm-up period relative to the taxiway portion is fairly straightforward to estimate. If the emission rate is approximately double for the first minute, then the warm-up phase "adds 1 min" to the idle phase. If the real time spent in the taxiway mode is 20 min, then the start-up emissions account for 5% of HC emissions that stem from the combined start-up + idle emissions. Due to the uncertainty in the composition of the emissions during the ignition phase, and the possibility that the aircraft analyzed in APEX3 is not representative of the fleet emission rate behavior, a more conservative estimate of the HAP emissions associated with "start-up" is < 10%. Further, it is important to note that the preceding analysis is based on comparing start-up emission indices to those at "ground idle." If the ICAO 7% idle is used as a reference point, correspondingly different ratios would result.

5.1.2 General Aviation

The general aviation category comprises aircraft that use piston engines, turbojet engines, and low bypass turbofan engines such as business jets. The VOC emissions of all of these are unregulated, and as a result are mostly unknown. Piston engine aircraft activity accounts for a small fraction of total fuel consumption at U.S. airports, however piston engines are the biggest source of airborne lead (Pb) from airports due to the continued use of leaded aviation gasoline ("AvGas"). For example, total throughput of AvGas at PHL in 2003 was 144,000 gallons, compared to 401,000,000 gallons of Jet Fuel A. Thus at most airports the contribution to total VOC emissions is minor. There are many general aviation airports in the U.S. at which piston engine aircraft are the most common type of aircraft, however, and so they are considered here. Although technically a criteria pollutant, lead is often included as a hazardous air pollutant as well. The most common grade of leaded AvGas is "100 LL," which has a maximum lead content 0.56 g Pb/L (Chevron 2006). Between 75% and 95% of the lead in the fuel is emitted in the exhaust; therefore lead

emission factors are quantitatively related to the lead fuel content and total lead emissions can be calculated to a high degree of certainty. For example, annual AvGas throughput at FLL in 2005 was 6x10^6 gallons (higher than most other commercial airports). The FLL environmental impact statement (Landrum and Brown 2007) used a fuel-based emission factor of 0.15 g Pb/L AvGas, which resulted in total Pb emissions (at the airport and aloft) of 3.7 tons, of which 14% (0.53 tons/year) appears on FLL's speciated HAP emissions inventory.

Very little is known regarding the emission of hydrocarbons from general aviation, though a recent study has been released by the Swiss Federal Office of Civil Aviation (Rindlisbacher 2007). This lack of knowledge regarding HAP emissions from piston engines represents a large information gap.

5.1.3 Activity Factors for Jet Engines

The ICAO databank also defines a standard landing/take-off cycle (LTO) by specifying the time spent in each mode. As illustrated in Figure 13, when the emissions vary by large factors with the operational state, knowledge of the time spent in each mode is crucial for accurately calculating the total emissions. A factor that often complicates the time-in-mode estimate involves the approach and climb-out phases. In the context of assessing airport-related HAP emissions, the climb-out and landing phases of an LTO are mostly minor since VOC emissions are dominated by the idle phase. Furthermore, approach emissions are spread out over a very large distance. In contrast, assessment of NO$_x$ emissions requires knowledge of the height of the mixing (boundary) layer and time in all LTO modes since NO$_x$ emissions increase with engine thrust. The ICAO certification data sheets use 3000 feet as a nominal mixing height, and defines the climb-out period as aircraft movement from a height of 500 ft up to 3000 ft and lasting 2.2 min. The true mixing height will vary with season, time of day, and daily meteorology, and therefore the true amount of time spent in climb-out phase will vary accordingly. Such accounting for time spent in climb-out and approach is not very relevant for assessing VOC/HAP emissions since the idle phase dominates the emissions of these species.

The fraction of total HAP emissions for an LTO is dominated by consideration of the "idle" mode (>90%). This is presented in Figure 13, in which the unburned hydrocarbon (UHC) emission rate (g/s) is plotted versus time during an LTO cycle. The total emission (g/LTO) from each LTO phase is equal to the area of the relevant "block." Evident is the predominance of the idle phase over the other phases as well as APU operation. Small deviations from the 7% ICAO thrust level at idle have large effects on the total HAP emissions during the idle mode. Evidence to date indicates that true ground
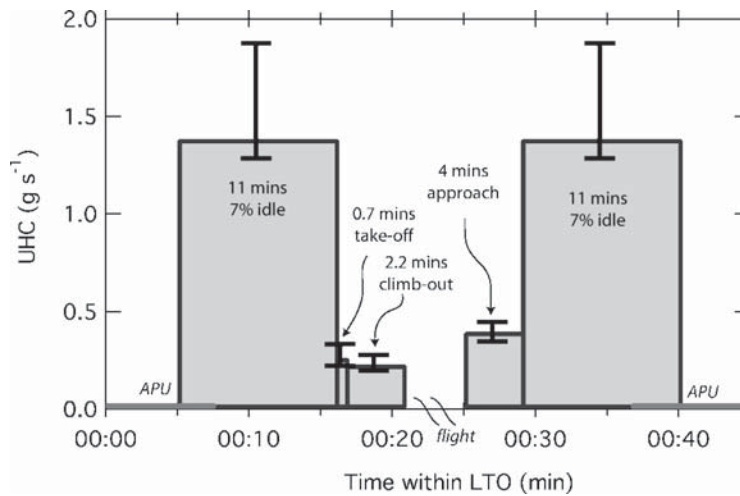
Figure 13. UHC (VOC) emissions during a landing/take-off cycle. The area of each block represents the total VOC emissions from that phase of a landing take-of cycle. VOC emissions are dominated by the idle phase. The error bars indicate the minimum uncertainty due to lack of knowledge regarding the true thrust values used and the temperature-dependence of VOC emissions.

idle for most aircraft is significantly less than 7%. Additionally, the emission indices of HAPs are greatly affected by ambient conditions (temperature, relative humidity) as discussed earlier. The error bars indicate the minimum uncertainty associated with those parameters.

In order to save fuel and reduce engine noise, some airports and airlines encourage the practice of single-engine taxiing, whereby one engine is shutdown while idling. According to the Chicago Department of Aviation, most planes at ORD engage in the practice (Johnsson and Washburn 2006), and American Airlines has publicized its use of single-engine taxiing (Arpey 2007). Furthermore, Boston Logan Airport recommended use of the practice on a voluntary basis, although its prevalence is unknown (Vanasse Hangen Brustlin 2006). Anecdotally the practice is considered to be uncommon.

Idle times are recorded by airports. Emission inventories, however, are based on annual averages and only express annual emissions. Such an annual average conveys little information that is relevant to acute effects, for example, the frequency of severe delays.

Outside the realm of HAPs is the criteria pollutant ozone (O_3), which is produced by photochemical reactions involving VOCs and NO_x. The NAAQS for ozone is an 8-hr average of 80 ppb. Nonattainment is based on the number of days in which the NAAQS is exceeded. Severe delays could also impact O_3 concentrations, yet to our knowledge there has been no investigation of the link between delays and number of instances when ozone NAAQS has been exceeded.

5.2 Airport Operations

5.2.1 Auxiliary Power Units

Auxiliary power units (APUs) are used to provide electrical power to an aircraft while on the ground so that the main engines can be turned off, and for starting the turbine engines. Total use of APUs is decreasing as jet bridges are commonly outfitted with 400 Hz plug-in electrical power and conditioned air. EDMS-recommended activity factors are 7 min when plug-in power is available and 26 min when it is not. The total emissions, even when used for 20 min, are negligible compared to other sources. APU emissions might be relevant to the exposure of passengers inside cabin air exposure or of ground service employees.

Measurements of APU emissions are available in the literature. Emission factors can be accessed through EPA's NONROAD inventory (which is used for EDMS when creating emission inventories).

5.2.2 Ground Support Equipment

Ground support equipment (GSE) consists of numerous vehicles such as belt loaders, baggage tugs, pushback vehicles, tractors, cabin service trucks (e.g., water, lavatory, catering, fuel trucks), de-icing vehicles, and airfield rescue and fire fighting equipment (ARFF).

EPA's NONROAD inventory and CARB's OFFROAD are the models most commonly used for creating emission inventories, similar to the case for APUs. GSE emission factors

are expressed in g/BHP-hr. Total emissions are calculated by the product of the time-in-mode for each type of GSE, the emission factor, the horsepower, and fractional load. The extent to which such off-road inventories accurately depict the emissions from GSE is unknown, as are the effects of fleet age and maintenance. Variation between real-world "fleet" GSE emission factors and database values, however, is likely small compared to that observed in the on-road fleet (discussed in Section 5.2.3). Whereas the fleet emissions of on-road vehicles are greatly influenced by vehicles with faulty emission control technology devices, the absence of such emissions control technology in most off-road engines implies that the variability is expected to be minor. Nevertheless, it is unclear if the off-road inventories used are appropriate for airport GSE fleets.

There are few peer-reviewed publications in the literature regarding GSE emission factors. Among them are a study of PAH emission factors from gasoline, diesel, and JP-8–fueled military GSE using chassis dynamometers and characterization by GC-MS. Much early work on characterization of GSE emission was done by the Air Force (Wade 2002).

Most airports employ a mix of gasoline and diesel-fueled GSE. The Inherently Low Emission Airport Vehicle (ILEAV) Pilot Program provided funds for replacement and/or upgrades of conventionally-fueled (gasoline/diesel) GSE to alternatively-fueled vehicles (FAA 2006). Upgrades of GSE fleets are becoming increasingly common, especially among airports located in polluted areas in nonattainment of the EPA's air quality standards (e.g., Dallas-Ft. Worth and LAX) (GAO 2003). Although no longer active, the ILEAV program has been succeeded by the FAA's Voluntary Airport Low Emission (VALE) program, which has been successful in encouraging the modernization of many airports' GSE fleets and applicable infrastructure.

5.2.3 Ground Access Vehicles

The GAV category consists of on-road vehicles driven on airport roadways, mostly for delivering airport passengers and employees to the airport terminals and buildings. It includes but is not limited to private passenger vehicles, taxis, shuttle vans (hotel, rental car, etc.), public transportation (buses), and security vehicles. It consists of a mix of gasoline, diesel, CNG, and electric-powered vehicles. Emission factors for emission inventories typically rely on EPA's MOBILE database, which relies on chassis dynamometer measurements. "Real-world" measurement techniques such as on-road remote sensing (Zhang, Stedman et al. 1995), tunnel measurements (Miguel, Kirchstetter et al. 1998), "chase" experiments (Herndon, Shorter et al. 2004; Herndon, Shorter

et al. 2005), and near-roadway ambient measurements (Miller, Hidy et al. 2006) provide an important supplement to the knowledge base. These real-world measurements have focused on criteria pollutants (CO, NO_x, etc.) and only few studies have made HAP measurements; however, their findings are relevant to HAP emissions as well.

Although few if any on-road remote sensing studies have been able to measure individual HAPs, they have been invaluable for providing information on the distribution of a fleet's emission factors. The most noticeable result revealed by remote-sensing measurements is that for modern gasoline-fueled cars, a small fraction of vehicles is responsible for most of the total emissions (Zhang, Stedman, et al. 1995). For example, in Denver (and many other locations) approximately 5% of the cars are responsible for 50% of the fleet CO emissions. These vehicles are known as "super-emitters" or "gross-emitters," and are usually the result of poor maintenance or in some cases emission-controls tampering. The emission rate of CO from a super-emitter can be 100 times higher than that from properly functioning vehicles. Similarly skewed distributions are observed for NO_x and hydrocarbon emissions. The relative importance of super-emitters is likely to increase in the future as vehicles become cleaner due to increasingly stringent emissions standards.

The accuracy of the GAV portion of EDMS-derived inventories depends on how well MOBILE can describe the actual fleet of vehicles at an airport. Since MOBILE's emission factors are based on dynamometer tests, assumptions regarding the frequency of super-emitters are required. The extent to which MOBILE accurately reflects any given airport fleet is unknown. A remote-sensing study at LAX from the mid-1990s (Klein and Saraceni 1994) indicated that the fleet of taxis operated by the Bell Cab Company contained a disproportionately large number of super-emitters; subsequent investigation revealed that significant emission-control device tampering had occurred. A similar study in the late 1990s found that taxis at ATL were among the dirtiest fleets recorded. The researchers' permission to operate on airport ground was even revoked after complaints from the taxi drivers (M. Rodgers 2007, personal communication). A different part of the same project found that New York taxis were relatively clean. This story highlights the challenges presented to MOBILE in accurately characterizing on-road emissions. These uncertainties are important for determining the risk of exposure groups such as airport employees that work close to the terminal ground traffic (as opposed to the airfield), but have little effect on overall airport emissions of gas-phase HAPs since aircraft at idle are the dominant HAP emitters.

Further findings regarding the accuracy of MOBILE were presented at the recent 16th Coordinating Research Council

(CRC) On-Road Vehicle Emissions Workshop (Cadle, Ayala et al. 2007):

1. MOBILE6 predicts hydrocarbon and NO emissions reasonably well for new vehicles, but underestimates hydrocarbon emissions from older vehicles;
2. MOBILE6 seriously underestimates hydrocarbon emissions at low temperatures; and
3. The relative importance of nontailpipe (evaporative) emissions is highly uncertain. On-road and source apportionment studies suggest that EPA and CARB models greatly overpredict the importance of evaporative emissions.

Another technique used to assess the accuracy of MOBILE relies on ambient measurements near roadways. Comparison of such ambient measurements with MOBILE6 has shown that there are significant flaws in the hydrocarbon speciation.

For example, the benzene/acetylene ratio of MOBILE6 is likely high by a factor of three based on comparisons with ambient measurements (Parrish 2006).

Further evaluations of the EPA's National Emission Inventory (including on-road, nonroad, and area VOC emissions) have been reviewed recently (Warneke, McKeen et al. 2007). Miller et al. states that our estimated confidence levels in on-road mobile HAP emissions are only "medium" (Miller, Hidy et al. 2006).

5.2.3.1 Activity Factors

The relevant activity factors for GAV depend on the desired level of inclusivity in an emission inventory. Some inventories such as those at IAD (DOT, FAA et al. 2005) include only on-airport complex miles traveled, whereas others such as PDX and ORD (FAA 2005; S. Hartsfield, personal communication) include much greater lengths of roads, depending on the purpose of the emissions inventory. MOBILE's emission factors are mileage-based, expressed in grams of pollutant per mile traveled. Since mileage-based emission factors tend to decrease with vehicle speed, some emission inventories meticulously divide the on-road sections into smaller segments and measure vehicle speed and total vehicle counts at each roadway segment (Vanasse Hangen Brustlin 2006). In such studies the uncertainty in the distribution of speeds is likely smaller than the uncertainty in the fraction of super-emitters at airports. When considering only on-airport miles traveled, total HAP emissions from GAV are minor

compared to total airport emissions, which are dominated by aircraft emissions at idle power.

5.2.4 Stationary Sources

Stationary sources at airports include airport power plants (HVAC systems), back-up electrical generators, parked motor vehicles (evaporative emissions), fuel storage and handling, airport restaurants, training fires, painting, solvent use, and engine run-up activity.

Although there are large variations in the size of stationary source VOC emissions in airport emission inventories, these inventories all indicate that HAP emissions are negligible and would have to be several orders of magnitude higher than currently believed for these sources to constitute a significant (>10%) source of HAPs. The speciated HAP emission inventories presented in the environmental impact statements from PHL, FLL, and ORD indicate stationary sources are of minimal importance. The one exception is toluene emissions at FLL, in which 12% of total toluene emissions are ascribed to painting activities, though we note that toxicity of toluene is low compared to other HAPs emitted at airports. The relevant national emission inventories are used for creating emission inventories (e.g., EPA's TANKS for emissions from fuel storage tanks).

Of the potentially large VOC (but not HAP) sources, the two largest contributions are from evaporative emissions from motor vehicles and fuel handling and storage. The VOC speciation of evaporative emissions closely resembles the fuel composition and is much different than that from exhaust emissions. VOC measurements at Zurich Airport (Schurmann, Schafer et al. 2007) revealed that evaporative emission plumes contained enhanced concentrations of aromatics and C2-C9 alkanes but no enhancement of alkenes compared to background concentrations. Oxygenated VOCs were not measured, but are likely negligible as Jet A contains a very small oxygenated content.

5.2.5 De-Icing Activities

The use of de-icing compounds is more a concern for water contamination than it is for air contamination. One study concluded that de-icing activities had a negligible impact on air quality (Celikel, Fleuti et al. 2003). Most environmental impact studies do not even address de-icing compounds in air quality chapters.

SECTION 6

Ambient Hazardous Air Pollutant Measurements

This section reviews the measurements of ambient HAP concentrations on or near airports and is divided this into three main categories: (1) inside terminal buildings, (2) on airport grounds, and (3) in nearby communities. Instead of presenting an exhaustive review of all known studies, we present only key results from various studies and refer to two excellent documents that present a more in-depth review of past measurement campaigns—the 2005 ORD final environmental impact statement (FAA 2005), and the 2003 FAA review (URS 2003).

6.1 Hazardous Air Pollutants Concentrations Inside the Airport

There are few measurements of HAPs inside airport buildings. Measurements of aldehydes in an airport in Strasbourg, France found a negligible difference between indoor and outdoor concentrations at the airport, though the outdoor concentrations were among the highest recorded at various outdoor locations. Average formaldehyde and acetaldehyde concentrations were 11 $\mu g/m^3$ and 4 $\mu g/m^3$, respectively (Marchand, Buillot et al. 2006). PAH measurements inside an Italian airport found benzo[b+j+k] fluoranthene and benzo [a]-pyrene concentrations to be of concern (Iavicoli, Carelli and Bergamaschi 2006). Other PAHs measured included naphthalene, 2-methylnaphthalene, 1-methylnaphthalene, and biphenyl.

6.2 Hazardous Air Pollutants Concentrations on Airport Grounds

Among the only peer-reviewed papers are measurements of CO, NO_x, and numerous VOCs from Zurich airport (Schurmann, Schafer et al. 2007). VOC measurements were limited to several "snapshot" measurements near the taxiway. Due to the limited number of measurements, it is hard to infer any information regarding average concentrations. For example, the benzene concentrations reported varied from 0.15 to 13.1 ppb.

During the recent APEX campaigns, most instruments used for the study sampled airport air continuously between dedicated engine tests and thus collected several days worth of data at OAK and Cleveland Hopkins International Airport (CLE). At the OAK site, the measurement team was set up at a ground run-up enclosure that was downwind of an active taxiway. As such, the site was exposed to advected exhaust plumes 10 to 60 sec in duration from idling aircraft. Over long time periods (more than 3 hr), the average concentrations were minimally affected by this intermittent component and were very close to the "background" concentrations. At times of heavy air traffic, however, the average concentrations could be significantly higher depending on the how often idling aircraft passed upwind of the site. For example, during one busy 45-min time period, the average concentration of formaldehyde was 2.4 ppb, compared to background concentrations of 0.6 ppb. These measurements show that the air at OAK is not well mixed, and that accurately quantifying the air quality at an airport would require measurements at numerous locations.

In contrast, the measurement site at APEX3 was situated on the outskirts of the airport property and no discernable aircraft exhaust plumes were observed. There has been little analysis of diurnal data taken at this site.

6.3 Hazardous Air Pollutants Concentrations in Adjacent Neighborhoods

Much more effort has been devoted to the measurement of HAPs in adjacent neighborhoods and at airport boundaries, with mixed results. Some measurements have shown that concentrations are no higher than in other urban settings (McGulley, Frick and Gilman, Inc. 1995), whereas others

have inferred an airport influence based on comparison of upwind and downwind measurements (Rhode Island Department of Environmental Management 2007). Most studies have relied on measurements with low temporal resolution and have struggled to identify the cause of the enhanced concentrations (aircraft versus nearby roads, etc). Most of the compounds emitted by aircraft exhaust (NO_x, CO, black carbon, VOCs, SO_2) are also emitted by other urban sources, particularly on-road vehicles. There are few if any unique tracer compounds that have been used to connect ambient measurements to airport emissions (which include both aircraft and vehicle emissions). Furthermore, a conclusion that demonstrates that pollutant concentrations near an airport are no higher than in other urban locations does not imply that the airport had no influence.

6.3.1 Discerning an Airport Influence on Elevated Concentrations

Results from the TF Green Air Monitoring Study at Providence Airport (PVD) (Rhode Island 2007) showed that no VOC concentrations exceeded the acute or chronic non-cancer health benchmarks at five sites near the airport in Warwick. Average concentrations, however, of benzene, 1,3-butadiene, formaldehyde, acetaldehyde, acetone, chloroform, carbon tetrachloride, and perchloroethylene exceeded the cancer benchmark levels. At all measurement sites, the concentrations of these HAPs were lower than at an urban measurement site in Providence. Since the chlorinated compounds are mainly caused by use of chlorinated solvents (as opposed to combustion sources such as aircraft or diesel exhaust), the Rhode Island Department of Environmental Management is inspecting sources of such solvents in the area. Inference of an airport influence based solely on the measured VOC concentrations and wind direction was inconclusive, mainly because the averaging time was 24 hr for most data (with some 3-hr samples) and thus correlations with wind speed were not very meaningful. However, 1-min averaged measurements of black carbon, which is emitted by both aircraft and diesel engines, showed a clear increase at the four measurement sites closest to the airport when the wind was blowing from the airport. Furthermore, the temporal profile of the elevation in black carbon measurements coincided with the increase in jet activity at the airport in the early morning. Further measurement studies and investigation of lung cancer data are planned.

In contrast, a suite of 24-hr average VOC measurements conducted for one month at various locations near Ted Stevens Anchorage International Airport was unable to discern a difference between upwind and downwind sites, and concluded that "Sites in and around airport tended to have lower BETX (benzene ethylbenzene toluene xylene) concen-

trations presumably because they were affected less by auto emissions." Only eight compounds were above the instrumental detection limit (Municipality of Anchorage 2003, 7).

Ambient pollutant concentrations were measured at Toronto's Lester B. Pearson International Airport (LBPIA) from May 2005 through April 2006 (Tradewind Scientific 2006). The purpose of the study was to assess the air pollution resulting from airport activities and aircraft operations. The study employed a mobile laboratory that was moved between five carefully chosen locations on the airport grounds. Stationary monitoring was conducted at each location for extended time periods. Mixing ratios of several pollutants were reported as hourly averages. The study continuously measured levels of CO, NO_2, NO, NO_x, O_3 and PM2.5 as well as wind speed, wind direction, and ambient temperature. In addition, total suspended particulates (TSP) and speciated hydrocarbon compounds were determined using samples acquired during 24-hr periods every sixth day. The measurement data were analyzed using a variety of methods including interspecies correlation, correlation with wind speed, and comparison with simultaneous measurements made at a nearby air quality monitoring station. This study did not focus on HAPs measurements though there is undoubtedly some information about HAPs emissions in the less frequent speciated hydrocarbon measurements.

The major conclusions of the study were that the measured pollutant concentrations at the airport are strongly affected by the background concentrations surrounding the airport and that this data set could be used for further studies of air pollution impacts, pollutant distribution, dispersion processes and emission chemistry. Also, the complete data set could be used to test dispersion models of the airport's pollutant emissions. One specific finding was that CO levels were elevated at the measurement site that was located on the apron near one of the terminals. Local sources at that location would probably include aircraft service vehicles, idling aircraft and the terminal itself. As the study concluded, further analysis of the measurement data is needed to draw stronger conclusions about source strengths and locations.

6.3.2 Source Apportionment

The 1999 study by KM Chng attempted to use "advanced chemical fingerprinting" to ascertain the influence of aircraft exhaust on soot deposition near ORD. The study concluded that samples collected near ORD more closely resembled on-road vehicle exhaust than they did aircraft exhaust (KM Chng 1999). Although this study focused on particulate matter, its findings on VOC emissions and concentrations were similar. This study was subsequently criticized by the Park Ridge studies (ENVIRON 2000).
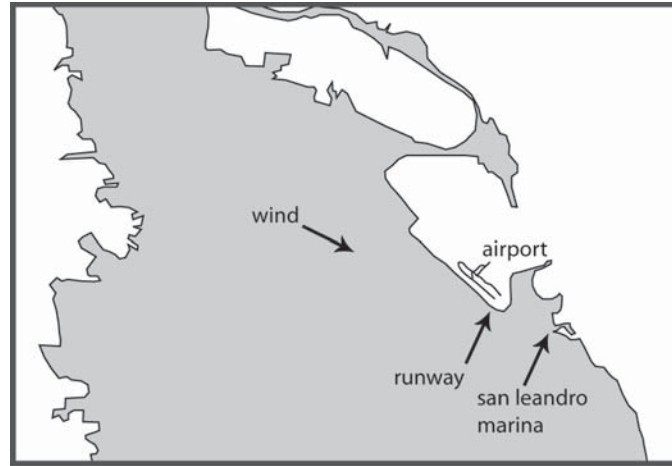
*Figure 14. San Leandro Marina and Oakland
International Airport.*
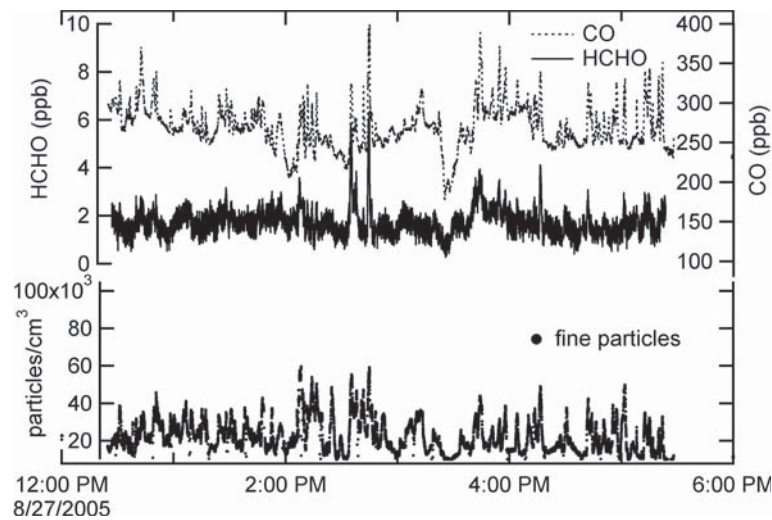
*Figure 15. Time series of measurements recorded 2 km
downwind of OAK.*

6.3.3 San Leandro Measurements

At the conclusion of the JETS-APEX2 study, the Aerodyne Mobile Laboratory spent two days at the San Leandro Marina (Figure 14), which is ~2 km downwind of the OAK runway. Winds were consistently from the northwest. Although limited in duration, these measurements are unique in that they enabled observations of diluted airport emissions with no interferences from non-airport sources, since there is no land in between the emissions and the measurement site.

A 6-hr time-series of HCHO, CO, NO_x, CO_2, and PM number concentration is shown in Figure 15. Individual air-craft exhaust plumes resulting from idle, take-off, and landing activity could be resolved. The average HCHO concentration in the time series shown is 1.3 ppb, while the interpolated background value is approximately 0.8 (similar to the background value observed on the airport grounds). More importantly, a dilution factor of ~5000 can be inferred for most of the observed plumes based on comparison of the observed CO_2 to known CO_2 concentrations at the exit of a high-bypass turbine engine. Such a simplified source-receptor scheme would be an ideal scenario for testing dispersion models.

Airport Dispersion Models and Predictions

A variety of models have been used for creating emission inventories and predicting pollutant concentrations at various locations near airports. Creation of emission inventories using the FAA's preferred dispersion model EDMS has been discussed in Section 3. Here the research team focused not on the intricacies of particular models but rather on the efficacy of using such models for predicting HAP concentrations.

7.1 Emissions and Dispersion Modeling System

The FAA's EDMS is a sophisticated model that has been periodically updated since its inception in the 1980s. As its inputs, EDMS creates emission factors for aircraft and relies on various EPA emission inventories for non-aircraft sources (e.g., MOBILE for on-road sources and NONROAD for APU and GSE emissions). EDMS relies on operator inputs for activity factors (e.g., time-in-mode, miles driven, etc.). The dispersion component of EDMS can be used to predict criteria pollutant concentrations at multiple locations near airports. Currently, EDMS does not incorporate chemistry in its calculations.

A Santa Monica Municipal Airport study eschewed EDMS in favor of the Industrial Source Complex Short Term (ISCST3) model (Piazza 1999). This study (Piazza 1999) criticized EDMS for various reasons, because of its "limited capabilities" to model the dispersion of toxic pollutants (versus criteria pollutants). Since 2000 EDMS has incorporated some limited lifetime modeling abilities similar to ISCST3, but it is still a minor capability and not designed for modeling of HAP concentrations.

Consideration of dispersion alone ignores the potentially important transformations that can occur due to atmospheric chemistry. Figure 16 depicts the atmospheric transformation of 1,3-butadiene in the atmosphere, which results in the formation of acrolein and formaldehyde. The time scale for this reaction can be as fast as 40 min under strong sunlight. With a wind speed of 3 m/s, roughly one-third of

emitted butadiene reacts to form acrolein and formaldehyde within 6 km of the source. Additionally, numerous VOCs, especially aromatic compounds such as toluene and xylene, are known to form secondary organic aerosol (particulate matter) following atmospheric oxidation (Ng, Kroll et al. 2007). The secondary aerosol formed by the oxidation of semivolatile compounds in diesel exhaust has been shown to greatly exceed that from the known aromatic precursors (Robinson, Donahue et al. 2007). The full extent to which the oxidation of aircraft exhaust leads to secondary aerosol is unknown.

Integration of chemistry into research-grade air quality models is an active field of research and is necessary for accurately predicting HAP concentrations that result due to airport emissions. Two current PARTNER projects (e.g., PARTNER Project 16, "Investigation of the Impacts of Aviation Emissions on Air Quality Impacts and PARTNER Project 11, "High-Priority Compounds Associated with Aircraft Emissions") are engaged in an ambitious effort to accomplish this goal. These projects are intended to provide an assessment of air quality impacts due to aviation emissions using a state-of-the-art comprehensive one-atmosphere air quality modeling system—the Community Multiscale Air Quality (CMAQ) model—which treats gas-phase chemistry and includes particulate matter (PM) and hazardous air pollutants (HAPs). To represent the distribution of aviation emissions accurately in air quality modeling, they are modifying the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system, which prepares emission inputs to CMAQ by including three-dimensional hourly direct emissions of CO, NO_x, THC, HAPs, SO_x, and PM2.5 processed by a research version of the FAA's EDMS. They plan to perform annual base and sensitivity CMAQ simulations at multigrid resolutions focused on a few U.S. airports, and to assess the contributions from commercial aircraft emissions to ambient air quality relative to the background air. They will also perform exploratory research to combine CMAQ outputs with local-
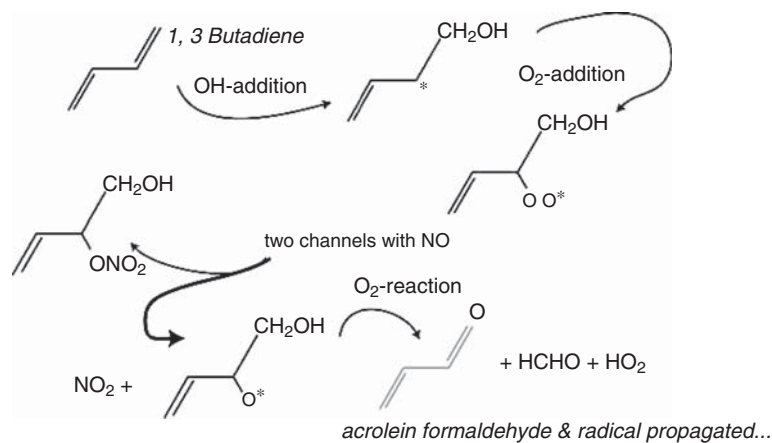
Figure 16. Atmospheric processing of 1,3-butadiene.

scale dispersion modeling to provide fine-scale details in the vicinity of the airports. The air quality outputs of this project will subsequently be used for health impacts analysis. Preliminary results from these projects are just becoming available.

Modeling studies in the peer-reviewed literature have focused on the criteria pollutants—O_3 (Pison and Menut 2004; Unal, Hu et al. 2005), particulate matter (Unal, Hu et al. 2005), and NO_x (Moussiopoulos, Sahm et al. 1997; Suppan and Graf 2000; Farias and ApSimon 2006) with scant attention to HAPs.

Two European models commonly used are the LASPORT Emission Calculation and Dispersion Model (German Airport Association) and ALAQS-AV (Airport Local Air Quality Studies). Comparisons of models are rare. One noticeable exception is the work of Celikel and co-workers (Celikel, Duchene et al. 2005), which compares emission inventories for Zurich Airport using three different methodologies. Few studies have combined modeling with concerted measurements, which would present a much-needed validation of the model outputs.

SECTION 8

Crucial Knowledge Gaps

Information gaps identified in this report are described in the following sections.

8.1 Emissions-Related Knowledge Gaps

These information gaps affect the accuracy of emission inventories (and any related health risk assessments).

8.1.1 Effect of Temperature on Aircraft HAP Emissions Near Idle

HAP emission rates can vary by well over a factor of 3 within the range of conditions encountered by many airports. There are no measurements at subfreezing temperatures, even though a significant portion of annual aviation activity occurs during such conditions.

8.1.2 Characterization of True Idle Levels and Times-in-Mode

Since the gas-phase HAP emissions are dominated by the idle phase, knowledge of actual idle times is necessary. Additionally, since the emission factor is a strong function of throttle setting, knowledge of the real-world power levels used are necessary. Emission indices for true ground idle (sometimes labeled 4%) can be a factor of 2+ greater than the 7% ICAO certification point. The likely distribution of throttle settings used as the aircraft progresses from the terminal to the runway (or the taxi-phase of an LTO) is unknown. This time-in-mode problem is probably highly variable and dependent on the frequency of flights. This problem does not lend itself to a simple relationship expressed as total emissions per LTO.

Since most emission inventories (i.e., those made under NEPA requirements) are required to consider average conditions and not worst-case scenarios, day-to-day variability or the impact of severe delays are not captured, nor is plane-to-plane variability. Any attempt to quantify the health risk posed by acute effects of HAPs must accurately account for situations in which emissions and concentrations are highest (e.g., long delays, low mixing heights, etc).

8.1.3 Full Characterization of HAP Emissions Near Idle Thrust

Measurements of HAP emissions indices have been performed at a limited number of power levels near idle (e.g., at APEX1,2,3 the common engine thrust settings were 4%, 7%, and 15%). A significant amount of interpolation is required to portray the effect of engine power on emission indices.

8.1.4 Single-Engine Taxiing

As discussed in Section 5.1.3, the prevalence of single-engine taxiing is unclear, though anecdotally is thought to be rare. If actually prevalent, this could have a large impact on emission inventories.

8.1.5 General Aviation Emissions Characterization

With the exception of lead emissions, which are well characterized, emissions from the general aviation category of piston engines are largely unknown.

8.1.6 Breadth of Measurements Across Engine Types

The APEX campaigns increased the total number of commercial turbofan engines characterized to more than 10. This is not necessarily a representative sample of aircraft engines. There are scant data on the variation of hydrocarbon emissions with engine age and maintenance history.

8.1.7 Uncertainties Persist in the Measurement of Reactive Aldehydes

Despite the apparent importance of acrolein, its quantitative detection remains elusive. This is true for glyoxal, methylglyoxal, and crotonaldehyde as well.

8.2 Dispersion Models and the Atmospheric Evolution of Hazardous Air Pollutants

The following knowledge gaps affect the airport community's ability to predict accurately HAP concentrations near airports, to discern the impact of airports on local air quality, and to identify which airport sources are most important for determining health risks.

8.2.1 Measurements of Ambient HAP Concentrations Near Airports

Even though numerous studies have focused on ambient HAP measurements near airports, the challenge of unambiguously assigning an airport contribution and quantifying source apportionment remains largely unmet. Few studies have been able to distinguish airport versus urban sources or aircraft versus non-aircraft sources, as they have mostly relied on VOC sampling with low temporal resolution (canister sampling with subsequent GC analysis). Furthermore, these studies have been limited in duration. Comparison with dispersion/chemistry models would be beneficial to both model validation and source apportionment.

8.2.2 Validation of Dispersion Models

The model currently required by the FAA for airport air quality assessments, EDMS, is inadequate for predicting atmospheric concentrations of HAPs since it does not possess any chemical transformation mechanisms. Without these mechanisms, concentrations of HAPs can only be predicted as if they were stable gases (similar to carbon monoxide). This is inappropriate and does not allow realistic assessments of exposure. The ability of any dispersion model, whether it incorporates such mechanisms or not, to predict accurately absolute concentrations of both criteria pollutants and HAPs at various locations near an airport must be validated with concerted measurements of pollutant concentrations.

8.2.3 Identification of the Emission Sources Most Important to On-Airport and Off-Airport Exposure

Although aircraft are generally the largest emission source of HAPs at an airport, they do not necessarily impact the health risk of various exposure groups the most, given the variation in the spatial and temporal relationship between the multiple airport emission sources (aircraft, GSE, terminal traffic, etc.) and potential exposure groups (e.g., nearby residents, airport-based workers, passengers). Identification of the emission sources that most greatly impact the health risk of various exposure groups has not been thoroughly examined.

8.3 Health Effects of Specific Hazardous Air Pollutants

In this section we discuss critical data gaps for HAPs with potentially significant exposures. Specifically, for several of the HAPs there are no currently established toxicity criteria, including for many of the low-molecular weight aldehydes, the alkenes 1-pentene and 1-hexene, and the petroleum hydrocarbon 2,2,4-trimethylpentane (2,2,4-TMP).

8.3.1 Glyoxal and Methylglyoxal

There is very little information regarding the toxicity of the aldehydes glyoxal and methylglyoxal. As discussed above, these aldehydes are mutagenic and may also be carcinogenic (IARC 1991; NEG 1995; Vaca, Nilsson et al. 1998). Glyoxal also has immunologic properties, can cause contact dermatitis, and is considered a strong human contact sensitizer (NEG 1995). There are no studies available, however, to evaluate effects of long-term exposure to either of these reactive aldehydes.

8.3.2 Low-Molecular Weight Aldehydes

There are very little data to evaluate the potential effects of long-term inhalation exposure to some of the low-molecular weight aldehydes that also have potentially significant exposures. These include the straight chain aldehydes propanal (propionaldehyde), butanal, and hexanal; and the 2-alkenal crotonaldehyde (butenal). Based on structural similarity to formaldehyde and acetaldehyde, the straight chain aldehydes could have carcinogenic potential, although this potential is expected to decrease with increasing molecular weight. In one study, crotonaldehyde induced liver tumors in rats exposed via drinking water (Chung, Tanaka, and Hecht 1986). The effect was not dose-related, however, which complicates interpretation of this observation.

8.3.3 Alkenes

There is very little toxicity information for several of the alkenes that also have potentially significant exposures, including for ethene, 1-butene, 1-pentene, and 1-hexene. For

this analysis the researchers identified only one chronic study for evaluating toxicity of ethene (Hamm, Guest, and Gent 1984) and one subchronic study for evaluating inhalation toxicity of 1-hexene (Gingell, Bennick, and Malley 1999). Additional chronic studies with ethene and 1-hexene in a different species would reduce uncertainty associated with potential toxicity of these two alkenes. We did not identify any studies for evaluating inhalation toxicity of 1-butene or 1-pentene.

8.3.4 2,2,4-Trimethylpentane

The research team only identified one study involving inhalation exposure to 2,2,4-TMP; it evaluated kidney toxicity of 2,2,4-TMP at only one exposure concentration (Short et al. 1989, as cited in U.S. EPA 2006). Short et al. found that 2,2,4-TMP promoted development of neoplastic lesions in the kidneys of male but not female rats. Results from other studies indicate that the ability of 2,2,4-TMP to induce kidney nephropathy is due to binding of 2,2,4-TMP to the protein alpha-2μ-globulin (e.g., Dietrich and Swenberg 1991), and EPA has concluded that kidney nephropathy associated with the alpha-2μ-globulin protein is relevant to humans (USEPA 1991d). Nonetheless, toxicity of 2,2,4-TMP should be evaluated in a subchronic or chronic inhalation concentration-response study, to determine whether there are effects in other tissues besides the kidney.

SECTION 9

Problem Statements

9.1 Dependence of HAP Emissions from Idling Aircraft on Ambient Conditions

AIRPORT COOPERATIVE RESEARCH PROGRAM PROBLEM STATEMENT

I.   PROBLEM TITLE
Dependence of HAP emissions from idling aircraft on ambient conditions

II.   RESEARCH PROBLEM STATEMENT
Frequently, commercial airport operators are asked to estimate the magnitude of toxic emissions from airport-related sources. These requests may come from government officials, courts, or concerned community groups. One of the key categories of potentially toxic emissions is Hazardous Air Pollutant (HAP) emissions—and the most important source of airport related HAPs compounds at most commercial airports is idling jet engines. This is because the HAPs emissions of modern jet engines are very small at power settings greater than idle. It is therefore critical to understand the rate of HAPs emissions at low power settings. These emissions will vary as a function of thrust setting, environmental variables (especially temperature), and engine type. In order to properly estimate airport HAP emissions it is necessary to better understand the aircraft engine emission factors as a function of these variables.

III.   OBJECTIVE
The goal of this project would be to improve our quantitative understanding of the largest aviation-related HAPs emission source—jet engines operating at low power. Emissions data for commercial aircraft are only available in the narrow temperature range (8 to 35 degrees Celsius [°C], 46–95 degrees Fahrenheit [°F]), and show that HAP emissions increase greatly with decreasing temperatures. The lack of knowledge regarding the temperature dependence of HAP emissions, and how it depends on engine technology, currently results in uncertainties of more than a factor of 2 in modeled HAP concentrations and risk. This is especially important for airports located in cold environments.

IV.   RESEARCH PROPOSED
This project would measure the emission rates of various HAPs compounds from commercial aircraft as a function of thrust level near idle and as a function of environmental variables such as temperature, humidity and pressure. The project should quantify HAPs emissions from a wide variety of in-service commercial aircraft under a wide variety of environmental conditions while operating in idle mode. It is envisioned that this will require making measurements during summer and winter to achieve as wide a temperature range as possible. Measurements at more than one airport are desirable. It is essential that the engine type and thrust setting be determined during these measurements to separate their effects from those of the environmental variables.

V.   ESTIMATE OF THE PROBLEM FUNDING AND RESEARCH PERIOD
Recommended Funding: $500,000
Research Period: 18 to 24 months

VI.   URGENCY AND PAYOFF POTENTIAL
This research will provide a detailed and quantitative understanding of jet aircraft HAPs emissions as a function of environmental and operational factors. The results will likely be incorporated in the U.S.

airport emissions modeling tool—Emissions and Dispersion Modeling System (EDMS). This will allow airport operators to utilize the latest scientific findings to construct HAPs emission estimates tailored to their specific airport. These estimates will be more defensible and better able to withstand litigation since they will be based on the latest scientific findings regarding jet engine HAPs emissions and the variables that affect them.

VII. RELATED RESEARCH
See ACRP 02-03 report.

VIII. PERSON(S) DEVELOPING THE PROBLEM
ACRP Project 02-03, PI: David Nelson (ddn@aerodyne.com, 978-663-9500).

IX. PROCESS USED TO DEVELOP PROBLEM STATEMENT
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ACRP Project 02-03, December 20, 2007, PI: David Nelson (ddn@aerodyne.com, 978-663-9500).

9.2 Characterization of Operational Thrust Levels

AIRPORT COOPERATIVE RESEARCH PROGRAM PROBLEM STATEMENT

I. PROBLEM TITLE
Characterization of operational thrust levels

II. RESEARCH PROBLEM STATEMENT
The International Civil Aviation Organization established and maintains the databank of engine certification data for all engines currently in commercial aviation use. The emissions component of the certification process defines four engine conditions and the associated thrust levels: idle (7%); approach (30%); climb-out (85%); and take-off (100%). Airport emission inventories for CO, NO_x, unburned hydrocarbons (UHC), and "smoke number" are routinely constructed using the certification emission indices, fuel flow rate, and time-in-mode data. While the overall time-in-mode is often known to some degree, there is significant evidence that the four certification thrust levels do not accurately mirror what is used during actual operation. Furthermore, emissions profiles are nonlinear with engine thrust settings. The emission rate of gas-phase HAPs at thrust

levels less than 7% can be more than twice as high as the emission rate at the certification value (7% thrust). Variation in the thrusts used during take-off can greatly impact NO_x emissions as well. Such differences in the emission rate with small changes in thrust level are sufficiently large to introduce large errors in emission inventories. Since airport operators use these emission inventories to evaluate mitigation strategies, the accuracy must be improved to reflect real-work thrust conditions.

III. OBJECTIVE
The principal objective of this research is to generate an input function for the Emissions Dispersion Modeling System that accurately reflects the distribution of thrusts used by aircraft at airports. Factors such as airport congestion, ambient conditions, and any effects of overall class of aircraft should be parameterized for simple implementation. The knowledge gained from this research will greatly improve the accuracy of emissions inventories.

IV. RESEARCH PROPOSED
The development of the real-world thrust profile will require an analysis of recorded fuel flow rates, the recorded "N1" parameter or other electronic data from a statistically significant number of landing, take-off cycles. The research will collect data from cooperative aircraft operators and merge with other datasets generated via the airport or other sources. This program will develop operational thrust distributions to be used in conjunction with emissions profile. The research will investigate the influence of anticipated factors on the real-world thrust profile (e.g., LTO/hr). The research will identify a simple approach to the parameterization of in-use thrust levels.

V. ESTIMATE OF THE PROBLEM FUNDING AND RESEARCH PERIOD
Recommended Funding: $50,000 to $75,000
Research Period: 12 months

VI. URGENCY AND PAYOFF POTENTIAL
This straightforward improvement to how inventories are constructed represents a very direct improvement to emissions management and understanding. As alternative emission mitigation strategies emerge, particularly those that target the ground idle and taxiing phases, an improved tool is mandatory to evaluate the benefits. This project would have a large payoff to airport emissions management and air quality modeling.

VII. RELATED RESEARCH

See ACRP 02-03 report. We are aware of some limited work in progress through the FAA/Partner research program. The product of that research we know of is an assessment of the impact of reduced thrust take-off on NO_x emissions. We are unaware of an effort to apply real-world thrust profiles to the hazardous air pollutant emissions.

VIII. PERSON(S) DEVELOPING THE PROBLEM

ACRP Project 02-03, PI: David Nelson (ddn@aerodyne.com, 978-663-9500).

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9.3 HAP Emissions from General Aviation Aircraft

AIRPORT COOPERATIVE RESEARCH PROGRAM PROBLEM STATEMENT

I. PROBLEM TITLE

HAP emissions from general aviation aircraft

II. RESEARCH PROBLEM STATEMENT

Frequently, general aviation airport operators are asked to estimate the magnitude of toxic emissions from airport-related sources. These requests may come from government officials, courts, or concerned community groups. One of the key categories of potentially toxic emissions is Hazardous Air Pollutant (HAP) emissions. HAP emission from general aviation aircraft are currently difficult to estimate because they have not been well studied and because there is no engine emission certification requirement for most general aviation aircraft. This is due to the relatively small size of their engines. Hence, HAP emissions (with the exception of lead) from aircraft piston engines, turbojet engines, and low-bypass turbofan engines (such as business jets) are largely unknown and should be quantified. In order to properly estimate airport HAP emissions from general aviation aircraft it is necessary to study these emissions with in-service aircraft.

III. OBJECTIVE

The goal of this project would be to improve our quantitative understanding of HAP emissions from general aviation aircraft. This project would support HAP emissions measurements of general aviation aircraft such as those employing piston engines, turbo-jet engines, and low-bypass turbofan engines (such as business jets). This information will be most important at general aviation airports.

IV. RESEARCH PROPOSED

This project would measure the emission rates of various HAPs compounds from general aviation aircraft. The project should quantify HAP emissions from a wide variety of in-service general aviation aircraft. It will be important to make measurements as a function of engine type and operational mode (idle, taxi, take-off). It is envisioned that this will require making measurements at more than one airport. It is essential that the engine type and operational mode be determined during these measurements to allow these measurement results to be incorporated in models that airport operators can use to estimate their emissions.

V. ESTIMATE OF THE PROBLEM FUNDING AND RESEARCH PERIOD

Recommended Funding: $400,000 to $500,000
Research Period: 18 to 24 months

VI. URGENCY AND PAYOFF POTENTIAL

This research will provide much needed measurements of HAP emission from in-service general aviation aircraft.

The results of this research will be used to produce more accurate emissions estimates for general aviation aircraft. These estimates will be more defensible and better able to withstand litigation since they will be based on the latest scientific findings regarding HAP emissions from general aviation aircraft.

VII. RELATED RESEARCH

See ACRP 02-03 report.

VIII. PERSON(S) DEVELOPING THE PROBLEM

ACRP Project 02-03, PI: David Nelson (ddn@aerodyne.com, 978-663-9500).

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9.4 Identification of the Emission Sources Most Important to On-Airport and Off-Airport Exposure

**AIRPORT COOPERATIVE RESEARCH
PROGRAM PROBLEM STATEMENT**

I. PROBLEM TITLE
Identification of the emission sources most important to on-airport and off-airport exposures

II. RESEARCH PROBLEM STATEMENT
Airports are an easily identified source of emissions within an urban or suburban setting. The emissions at airports come from jet engines, ground support vehicles, the airport facilities themselves and from ground access vehicles arriving at or departing from the airport grounds. Due to the high visibility of the airport and the activity it supports, it is frequently challenged to provide a self-assessment of its emissions and impact on the surrounding neighborhoods and environment. The emissions at airports are spatially inhomogenous, vary diurnally, and very likely have seasonal dependence. As a result, annual tabulation of net emissions, summing multiple sources is not adequate to understand what emissions sources influence exposure.

III. OBJECTIVE
The purpose of this project is to identify which emission sources (aircraft, GSE, terminal traffic, etc.) most greatly affect potential receptors (e.g., nearby residents, airport-based workers, passengers). This will include apportionment among the various airport sources (e.g., aircraft, GSE, GAV) and non-airport sources. Measurements used in conjunction with predictive models will provide a quantitative evaluation of the accuracy of models. Models used to predict the concentrations of HAPs near airports have not been adequately tested.

IV. RESEARCH PROPOSED
This should be done using dispersion/chemistry models tested against complementary measurements.

Conclusive deduction of source apportionment will require coordinated measurements of the main combustion gases (CO_2, CO, NO, NO_2), speciated HAPs (e.g., benzene, formaldehyde, etc.) and PM (characterized by number/size, mass, and chemical composition). Source apportionment is required to evaluate proposed emissions mitigation strategies. This project will help airport operators to identify the "low-hanging fruit" with regards to minimizing the health risk presented by the various emission sources present at an airport.

This research will necessarily involve the integration of measurements and models over multiple spatial and temporal scales. Different exposure groups being considered may require different model, inventory, and measurement demands. The exposure of a curbside check-in worker is very different from that of ground support workers. The proposed research will identify the exposure groups to be evaluated and develop appropriate assessments for each.

V. ESTIMATE OF THE PROBLEM FUNDING AND RESEARCH PERIOD
Recommended Funding: $500,000-$750,000
Research Period: 24-36 months

VI. URGENCY AND PAYOFF POTENTIAL
Successful execution of the proposed work will gain a genuine understanding of how airport emissions affect different exposure groups.

VII. RELATED RESEARCH
See ACRP 02-03 report.

VIII. PERSON(S) DEVELOPING THE PROBLEM
ACRP Project 02-03, PI: David Nelson (ddn@aerodyne.com, 978-663-9500).

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SECTION 10

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A B B R E V I A T I O N S   A N D   A C R O N Y M S

APEX	Aircraft Particle Emissions eXperiment
APU	auxiliary power unit
ATSDR	Agency for Toxic Substances and Disease Registry
BMC	benchmark concentration
BMCL	lower 95% confidence limit on the benchmark concentration
BOS	Boston Logan International Airport
CARB	California Air Research Board
CIIT	Chemical Industry Institute of Toxicology
CO	carbon monoxide
CO_2	carbon dioxide
EDMS	Emissions and Dispersion Modeling System
EI	emissions index
EPA	U.S. Environmental Protection Agency
EtO	ethylene oxide
FAA	Federal Aviation Administration
FLL	Fort Lauderdale Hollywood International Airport
GAV	ground access vehicles
GSE	ground support equipment
HAP	hazardous air pollutant, also known as "air toxics." In the context of this report, particulate matter is excluded
HBEL	health based exposure level
HC	hydrocarbon
HCHO	formaldehyde
HEC	human equivalent concentration
HVAC	heating, ventilating, and air-conditioning
ICAO	International Civil Aviation Organization
ILEAV	Inherently Low Emission Airport Vehicle Pilot Program
IRIS	Integrated Risk Information System
ISCST3	Industrial Source Complex Short Term Model
IUR	inhalation unit risk
LOAEL	lowest observed adverse effect level
LTO	landing take-off
MDW	Chicago Midway Airport
mg/m^3	milligrams per cubic meter
MRL	minimum risk levels
NAAQS	National Ambient Air Quality Standards
NEPA	National Environmental Protection Act
NMHC	nonmethane hydrocarbons
NO_2	nitrogen dioxide
NOAEL	no observed adverse effect level
O_3	ozone
OAK	Oakland International Airport
OEHHAT	Office of Environmental Human Health Assessment Toxicity
ORD	Chicago O'Hare International Airport
PAH	polycyclic aromatic hydrocarbon
PARTNER	Partnership for AiR Transportation Noise & Emissions Reduction
Pb	lead
PDX	Portland International Airport
PHL	Philadelphia International Airport
pptv	parts per trillion by volume
ppbv	parts per billion by volume
ppmv	parts per million by volume
ppmw	parts per million by weight
RBC	risk-based concentration
REL	recommended exposure limit
RfC	reference concentration
RIVM	National Institute for Public Health and the Environment of the Netherlands
SIP	State Implementation Plan
SO_2	sulfur dioxide
TC	tolerable concentration
TERA	Toxicology Excellence in Risk Assessment
THC	total hydrocarbon
tons	Emission inventories in the U.S. traditionally express mass in tons, which is an ambiguous term since there are three types of tons: metric tons (2,200 lbs), imperial tons (2,240 lbs), and short tons (2,000 lbs). In this document the term "ton" refers to short tons.
TPHCWG	Total Petroleum Hydrocarbon Criteria Working Group
TSP	total suspended particulate
UHC	unburned hydrocarbon. This term is slightly misleading since some HC emissions from aircraft are better described as "partially" burned (e.g., aldehydes)
VALE	Voluntary Airport Low Emission program
VOC	volatile organic compound. According to the EPA, (s) "Volatile organic compounds (VOC) means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions. This includes any such organic compound other than the following, which have been determined to have negligible photochemical reactivity: Methane, ethane, methylene chloride, CFCs, HFCs, HCFCs". From www.epa.gov/ttn/naaqs/ozone/ozonetech/def_voc.htm.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation