Preliminary Assessment of the Impact of Commercial Aircraft on Local Air Quality in the U.S.

by

Gayle L. Ratliff

B.S. Physics
Florida State University, 2002

SUBMITTED TO THE ENGINEERING SYSTEMS DIVISION IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2007

Signature of Author: ______________________
Technology and Policy Program, Engineering Systems Division
May 23, 2007

Certified by: ______________________
Ian A. Waitz
Jerome C. Hunsaker Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by: ______________________
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

Preliminary Assessment of the Impact of Commercial Aircraft on Local Air Quality in the U.S.

by

Gayle L. Ratliff

Submitted to the Engineering Systems Division on May 23, 2007
in Partial Fulfillment of the Requirements for
the Degree of Master of Science in Technology Policy

Abstract

This thesis examines the impact of aircraft emissions on local air quality by performing two analyses: an assessment of U.S. commercial aircraft contribution to county budgets of primary pollutants in nonattainment areas, and an assessment of the health effects caused by commercial aircraft emissions that serve as precursors to changes in ozone and ambient particulate matter (PM).

Based on 148 airports located in 134 counties, this work found that for the base year 2002, the commercial aircraft contribution to county budgets of primary pollutants of CO, NO_X, SO_X, VOCs, $PM_{2.5}$, and PM_{10} ranged from less than 0.01% to as high as 36.36% with an average contribution of 0.82%. The average contribution for CO was found to be 0.81%, NO_X 1.73%, SO_X 1.39%, VOCs 0.67%, $PM_{2.5}$ 0.24%, and PM_{10} 0.07%.

In general, this research found public health detriments resulting predominantly from $PM_{2.5}$ related to aircraft emissions. However, the inventories used for the health impacts analysis are not consistent with the inventories that are described above and have several known errors. Therefore the results are presented only to illustrate the methodologies rather than as a good estimate of the health impacts. Notably, ozone disbenefits occurred with the removal of aircraft emissions of NO_X. Urban cores experienced increased levels of ozone resulting in a net increase in incidences of ozone-related health endpoints.

There are several limitations to the work described in this thesis. In particular, the inventories used for assessing the health impacts may be in error by as much as ±50% and the air quality simulations were completed for only 4 months of the year. Therefore, the primary contribution of this thesis is in providing a description of the methodologies that will be used later within a more comprehensive study.

Thesis Supervisor: Ian Waitz
Title: Jerome C. Hunsaker Professor of Aeronautics and Astronautics

Acknowledgements

This research was funded under FAA Contract Number: DTFAWA-05-D-00012.

This work would not be possible without the help of the following researchers:
Don McCubbin, Abt, Associates
Stephen Lukachko, MIT
Melissa Osfeldt, CSSI, Inc.
Ralph Iovinelli, FAA Office of Environment and Energy
Christopher Sequeira, MIT
Sarav Arunachalam, University of North Carolina
Mike Graham, Metron Aviation

Thank you to Warren Gillette of FAA.
Thank you to Laurel Driver of EPA.

Thank you to Professor Ian Waitz for believing in my abilities and for teaching me to tackle problems with integrity and with a realistic optimism.

Thank you to Spencer Lewis and Amon Millner for helping with all of the miscellaneous problems I encountered while conducting this research.

Thank you to my parents for your unending encouragement.

This work is dedicated to my sisters.

Table of Contents

List of Figures

List of Tables

1.0 Background

The Energy Policy Act of 2005 (H.R. 109-90, Section 753) requires the Administrator of the Environmental Protection Agency (EPA) and the Administrator of the Federal Aviation Administration (FAA) to initiate a study to identify ways to reduce aviation fuel burn and emissions that affect local air quality. The study must focus on air traffic management inefficiencies with considerations of aircraft safety and security; noise; as well as, effects on human health. Specifically, the mandate requires the study to identify:

- The impact of aircraft emissions on air quality in nonattainment areas;
- Ways to promote fuel conservation measures for aviation to enhance fuel efficiency and reduce emissions; and
- Opportunities to reduce air traffic inefficiencies that increase fuel burn and emissions.

The Study is being conducted by the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), an FAA/NASA/Transport Canada-sponsored Center of Excellence, on behalf of the FAA and EPA, with coordination and partnership with two contractors, CSSI Inc. (CSSI) and Metron Aviation (Metron). Other project participants include the University of North Carolina, the Harvard School of Public Health, and the U.S. Department of Defense.

This thesis is a preliminary assessment of the first of the aforementioned objectives: a determination of the impact of aircraft emissions on local air quality. Because of limitations of the underlying emissions inventories and air quality simulations, the primary contribution of this work is in describing the methods that will be used for a more complete assessment that is on-going, rather than as a basis for preliminary findings on local air quality impacts of aviation. This research builds upon the work of other study participants and reflects only a portion of the work necessary to fulfill the requirements of the Energy Policy Act. The final recommendations as to ways to promote fuel conservation will synthesize the results from all objectives and will appear in the Final Report of the Energy Policy Act Study. Figure 1 depicts the objectives of the Energy Policy Act Study. The focus of this thesis will be on the left column: a description of the methods to determine the impact of aircraft emissions in nonattainment areas.

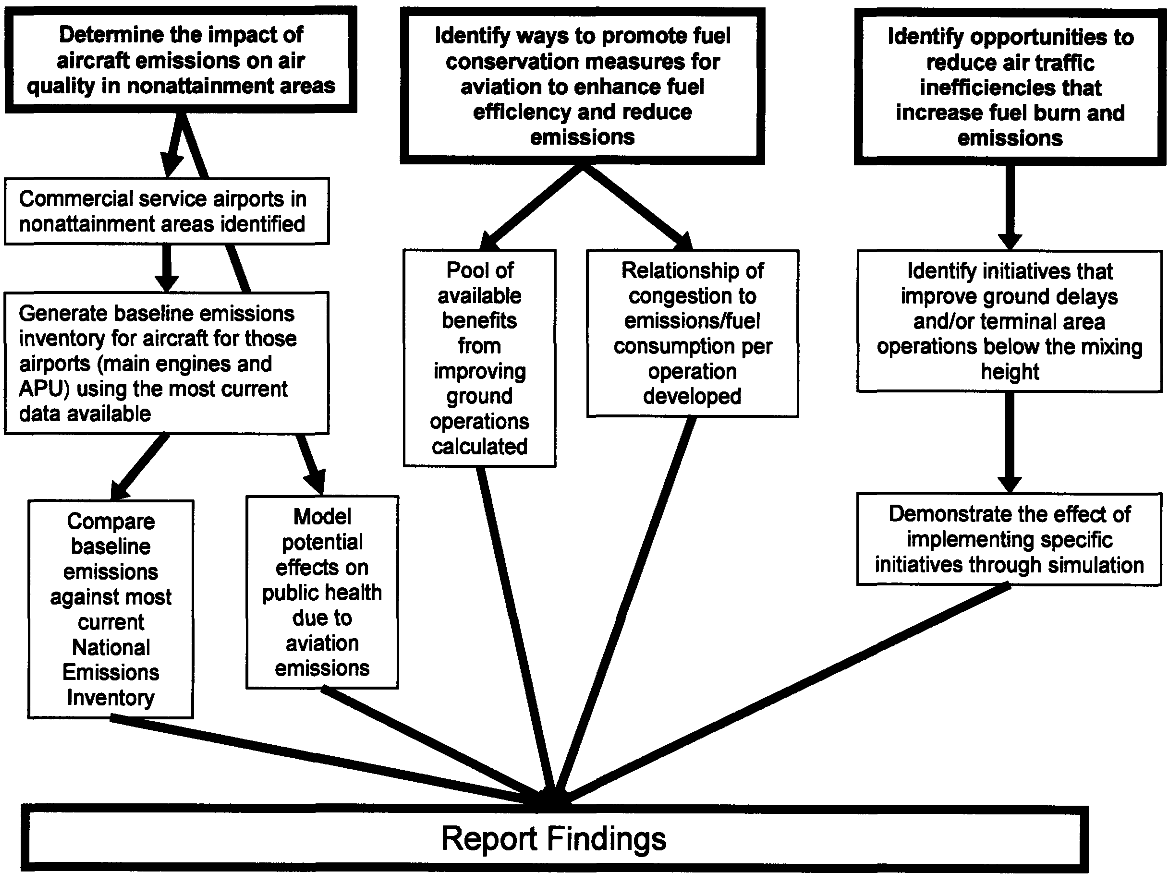

Figure 1. Overview of the Energy Policy Act Study

2.0 Motivation: Assessing the Impact of Commercial Aircraft on Local Air Quality

The Clean Air Act requires the EPA to set standards for ambient levels of pollutants that have been shown to have negative impacts on human health and welfare ("Clean Air Act Amendments," 1990). The EPA currently sets standards, National Ambient Air Quality Standards (NAAQS), for six key pollutants: ozone, particulate matter, carbon monoxide, nitrogen dioxide, sulfur dioxide, and lead. These pollutants are known as *criteria pollutants* because standards are set by developing human health-based and environmental-based criteria from scientific studies.

Primary standards are set to protect public health and *secondary standards* are set to protect public welfare, including crop damage and decreased visibility. These standards determine the maximum concentration of the pollutant acceptable over a variety of averaging times dependent on the scientific literature. Areas that do not meet primary standards are called *non-attainment* areas.

To achieve these standards, the Clean Air Act requires the EPA to set emissions standards for numerous mobile sources including aircraft. Aircraft jet engines emit carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_X), carbon monoxide (CO), oxides of sulfur (SO_X), unburned hydrocarbons, particulate matter ($PM_{2.5}$), and other trace compounds. While most of an aircraft's operation takes place at altitudes where emissions do not directly affect local air quality, emissions of pollutants below the atmospheric mixing height contribute to local inventories of criteria pollutants.

US Commercial aircraft emissions standards have been in place for over 30 years. The EPA has set emission standards for:

- Engine smoke and fuel venting, 1974
- Hydrocarbon emissions, 1984
- NOx and carbon monoxide, 1997

In 2005 the EPA amended existing engine NO_X certification standards, imposing an approximate 16% reduction from 1997 standards (*EPA Regulatory Announcement*, 2005).

The International Civil Aviation Organization (ICAO), an international organization created in 1972 by the United Nations Conference on the Human Environment, was formed to "achieve maximum compatibility between the safe and orderly development of civil aviation and the quality of the human environment" ("ICAO Annex 16," 1993). ICAO has served as one of the lead organizations in the development of standards and procedures for certifying aircraft engines, and the US is one of 188 participatory member states. While ICAO standards are not enforceable, any member state that does not adopt a standard must provide a written statement if national regulations and practices are not equal to or more stringent that those set by ICAO. The 2005 EPA NO_X standards were set to be consistent with ICAO standards, and the rule signals growing harmonization between US and international practices.

There are several areas of growing concern stemming from the effects of aircraft emissions on local air quality.

One area of increasing importance and high uncertainty is the effect of aircraft emissions on county inventories of fine particulate matter (Waitz, Townsend, Cutcher-Gershenfeld, Greitzer, & Kerrebrock, 2004). Particulate matter (PM) refers to the complex mixture of solid particles and liquid droplets, or solid particles coated with liquid, that remain suspended in air. Urban air contains PM composed of a number of components including acids (nitrates and sulfates), organics (hydrocarbons), soot, and dust. Particulates smaller than 10 micrometers (μm) are classified as PM_{10}. Particulates smaller than 2.5 μm are classified as $PM_{2.5}$. *Primary PM* is directly emitted from combustion sources and consists primarily of carbonaceous material (e.g. soot and organics). *Secondary PM* forms in the atmosphere from reactions involving precursor gas emissions. In the urban atmosphere, secondary PM forms primarily as a result of precursors, sulfur and nitrogen oxides (NO_X and SO_X).

EPA has introduced increasingly stringent standards for particulate matter emissions for a number of mobile sources including passenger cars, light trucks, and large passenger vehicles (*Draft RIA Tier 2 Motor Vehicle Standards*, 1999) and has recently proposed a rule expected to reduce $PM_{2.5}$ emissions from locomotive and marine diesel engines by 28,000 tons by the year 2030 (*Draft RIA Locomotive & Marine Rule*, 2007). EPA has also targeted PM precursor emissions most recently with the Clean Air Interstate Rule (CAIR) which permanently caps emissions of SO_X and NO_X from power plants. CAIR was promulgated by EPA in 2005 and is expected to reduce power plant SO_2 emissions by 70% and NO_X emissions by 60% from 2003 levels once fully implemented. (*Clean Air Interstate Rule*, 2007).

Despite these pending reductions from other sources, there are currently no uniformly accepted methods for estimating PM and PM precursors from aircraft. Data limitations and inadequate scientific understanding have prevented comprehensive estimation of both the volatile and non-volatile PM components and the aviation community continues work to characterize and measure PM emissions from aircraft engines, and if necessary adopt strategies to reduce them.

The effect of particulate matter on human health is an area of growing research. Exposure to particulates has been linked to various adverse health effects including asthma, bronchitis, acute and chronic respiratory symptoms such as shortness of breath and painful breathing. Long term exposure to particulates has also been linked to premature deaths. Fine particles can travel thousands of miles from emission sources and regional transport contributes to concentrations from non-local sources. The EPA estimates that 88 million people live in areas that do not meet the current U.S. standard for $PM_{2.5}$ (*EPA Green Book*, 2007). Figure 2 shows U.S. $PM_{2.5}$ nonattainment areas.

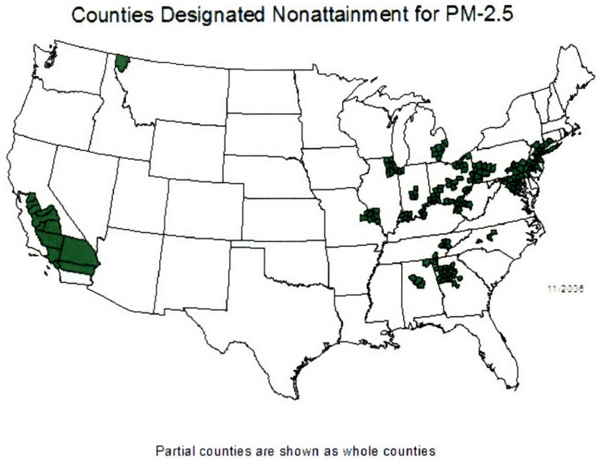

Figure 2. $PM_{2.5}$ Non-attainment areas *(EPA Green Book, 2007)*

Aircraft emissions of NO_X are another key driver in concerns over local air quality impacts. Ozone is not emitted directly into the ambient air but is formed when oxides of nitrogen from combustion and volatile organic compounds (VOC's), a broad range of carbon-based compounds, react in the presence of sunlight. While aviation NO_X emissions per passenger mile have decreased, total emissions have increased due to aviation's considerable growth in the last decade (FAA, 2005). The EPA recently amended existing NO_X standards for new commercial aircraft engines in part because of aviations increasing contribution to ozone noncompliance (*EPA Regulatory Announcement*, 2005). While on-road NOx emissions are also expected to decrease, reduction in aircraft emissions pose a challenge (FAA, 2005).

There are numerous health effects associated with increased levels of ozone. Ozone exposure reduces the respiratory system's ability to fight off bacterial infection, and has been linked to respiratory diseases such as asthma, emphysema, and bronchitis. Long-term, repeated exposure to ozone can irreversibly damage the lungs, and recent research also suggests that acute exposure to ozone likely contributes to premature death (*NOx Budget Trading Program, 2005 Program Compliance and Environmental Results*, 2006). The EPA estimates that 157 million people live in areas that exceed the 8-hr ozone standard (*EPA Green Book*, 2007).

The EPA designates areas that have a history of nonattainment but are currently meeting standards as *attainment with a maintenance plan*, or *maintenance areas*. Figure 3 shows all of the counties that are entirely or partially in nonattainment or maintenance areas for the 8-hr ozone standard.

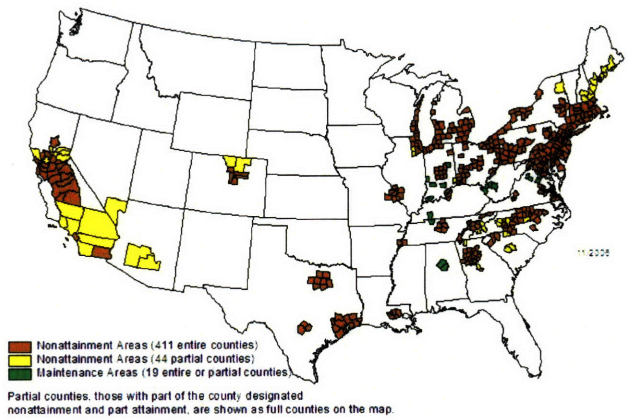

Figure 3. Ozone Nonattainment and Maintenance Areas *(EPA Green Book, 2007)*

The effects of aircraft emissions of NO_X, PM, and other primary criteria pollutants may be influenced by the fact that the worst local air quality generally occurs around the congestion of cities, which are often centers for aviation activity (FAA, 2005). It is estimated that 122 million people nationwide live in nonattainment areas for at least one of the six principle pollutants (*EPA Green Book*, 2007). Figure 4 shows the 150 major commercial airports currently located in ozone, PM, and/or CO non-attainment and maintenance areas (Gillette, 2006).

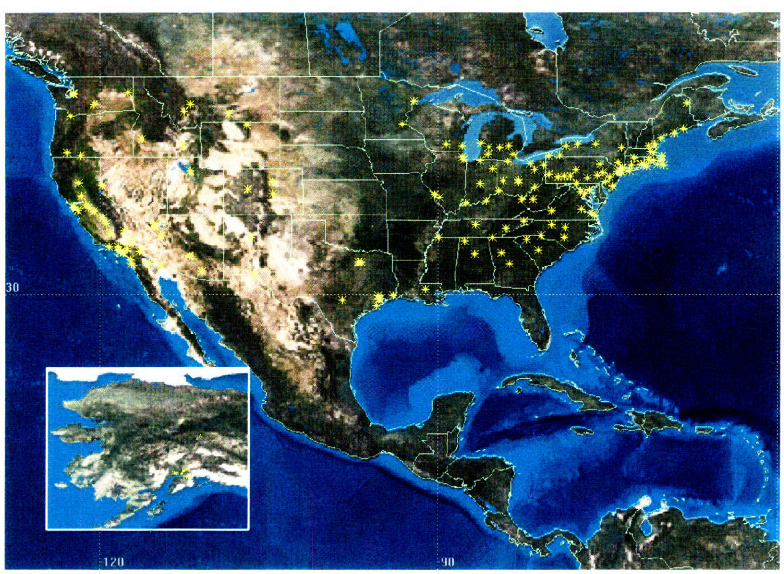

Figure 4. Commercial Service Airports Located in Ozone, PM, and/or CO Non-attainment and Maintenance Areas

This thesis examines the impact of aircraft emissions on local air quality by performing two preliminary analyses:

- An assessment of commercial aircraft contribution to county budgets of primary pollutants in nonattainment areas, and
- An assessment of the health effects caused by commercial aircraft emissions that serve as precursor to ozone and $PM_{2.5}$

Because of limitations of the underlying emissions inventories and air quality simulations, the primary contribution of this work is in describing the methods that will be used for a more complete assessment that is on-going, rather than as a basis for preliminary findings on local air quality impacts of aviation.

The first chapter focuses specifically on airports in nonattatinment counties to characterize the relative contribution of aircraft emissions to total county emissions. This chapter will deal with the challenges of creating an accurate aircraft emissions inventory, specifically the difficulty in estimating aircraft PM and the assumptions necessary to account for aircraft auxiliary power unit (APU) emissions.

The second chapter, an analysis of the health impacts resulting from commercial aircraft emissions, deals with virtually all commercial service airports, as harmful emissions from upwind counties affects those counties classified as nonattainment. This chapter will detail the atmospheric modeling that was done to estimate changes in ambient concentrations of ozone and $PM_{2.5}$ and to simulate the dispersion of these pollutants around airports, as well as detail the analysis performed to determine the subsequent effects on public health.

3.0 Aircraft Contribution to County Emissions Inventories

Aircraft jet engines emit carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_X), carbon monoxide (CO), oxides of sulfur (SO_X), unburned hydrocarbons (HC), particulate matter ($PM_{2.5}$), and other trace compounds. While most of an aircraft's operation takes place at altitudes where emissions do not affect local air quality, aircraft emissions released below the mixing height (Earth's boundary layer) contribute to local ambient pollutant concentrations and are quantified in local/regional inventories.

Aircraft engines are not the only source of emissions associated with air transportation. Vehicles transporting passengers to and from an airport, stationary power sources, aircraft ground support equipment, fuel handling and storage, emergency response training fires, and airport-specific construction equipment all contribute to the sum of emissions. Another source of aircraft emissions is auxiliary power units (APU's), small self-contained generators that provide electricity and air conditioning to aircraft parked on the ground.

The Federal Aviation Administration's (FAA) Emissions Dispersion Modeling System (EDMS) is capable of estimating airport emissions from all aviation sources. EDMS provides emissions inventories and dispersion calculations to assess the air quality impacts of airport emissions. EDMS estimates emissions from aircraft engines and APU's based on the aircraft type and the associated model-specific engines and APU's typically installed on aircraft according to aircraft registration data. Aircraft weight, aircraft taxi and ground delay time, airport meteorological conditions, and airport field elevation impact the quantity of emissions estimated for a unique aircraft/engine combination.

Inputs to EDMS are obtained from a number of sources including:

- ICAO Engine Emissions Certification Databank
- FAA's National Airspace System Resources (NASR)
- FAA's Integrated Noise Model (INM)
- Manufacture APU emissions performance data
- FAA's Aviation Environmental Design Tool (AEDT) Airport Database[1]

EDMS computes total aircraft emissions of PM, CO, hydrocarbons,[2] NO_x, and SO_x for all phases of taxi and flight based on International Civil Aviation Organization (ICAO) engine emissions indices, the mass of pollutant produced (e.g, mg) per amount of fuel consumed (e.g. kg), contained in the ICAO Engine Emissions Certification Databank.

[1] AEDT is an airport analysis tool being developed by FAA with the ability to model noise and emissions simultaneously. The first phase of development has been completed and the underlying systems data including airport elevation and meteorological conditions processed through AERMET, EPA's meteorological data processor.

[2] Non-methane hydrocarbons (NMHC) & Volatile organic compounds (VOC's)

The EDMS emissions processor computes aircraft landing-takeoff cycle (LTO) emissions based on aircraft performance parameters, operational mode assumptions and engine-type specifications. Figure 5 depicts the inputs to EDMS.

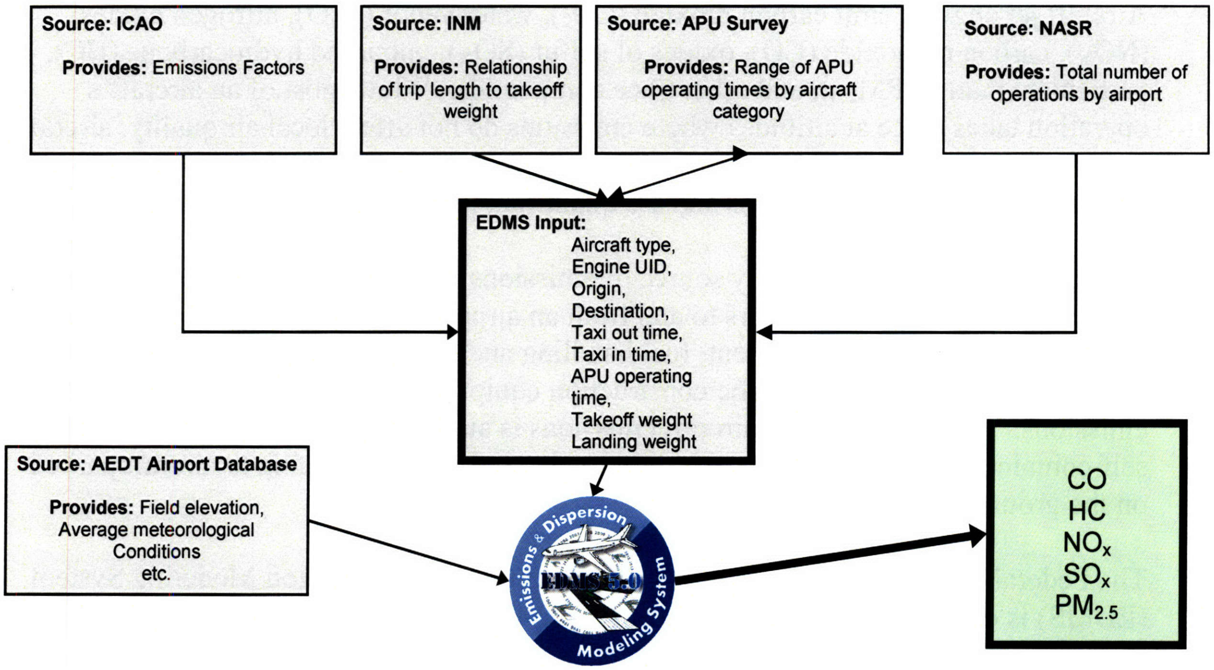

Figure 5. EDMS Inputs

EDMS is continually updated under the guidance of government, industry, and academia. This chapter covers research conducted for the Energy Policy Act Study aimed at improving the estimation of total particulate matter emissions from aircraft and the APU usage assumptions built into EDMS. This chapter describes the specific models and assumptions integrated into EDMS to create an accurate baseline inventory of primary pollutants. The final sections will provide greater detail of the EDMS baseline runs produced by CSSI under these improved assumptions, and provide an assessment of the relative contribution of commercial aircraft to total county budgets of primary pollutants.

3.1 Estimating Particulate Matter from Aircraft

One of the chief research objectives to support the Energy Policy Act Study was to address the challenges of modeling aircraft particulate matter emissions.

Aircraft engines directly emit *primary* PM. *Secondary PM* is formed when gaseous emissions undergo chemical reactions in the ambient air before forming in the cooling exhaust plume. Many processes including gas-to-particle conversion, condensation of gaseous species on existing primary particles, and coagulation of new particles can lead to secondary PM.

Aircraft PM consists of both non-volatile and volatile particles. *Non-volatile PM* (nvPM) consists of solid particles composed chiefly of carbonaceous particles but can also include other metal or ceramic particles. *Volatile particulate matter* (vPM) refers to volatile condensate formed in the exhaust as it cools or directly emitted as engine lube oil.

Historically, total PM from aircraft has been difficult to estimate due to the lack of physical understanding and the difficulty of measurement. In the past aviation PM has been represented by substituting diesel emissions, by using data from a small sample of engines, and by using a limited number of emissions tests from older military aircraft (Iovinelli, 2005). However, these estimates have proven to be inaccurate representations due to differences in fleet composition and aircraft engine characteristics. Improved data and greater scientific understanding have allowed for more accurate aircraft PM estimates in recent years.

Aircraft engine PM emissions are influenced by numerous factors including fuel flow, engine design, operating conditions, and fuel composition. Aircraft PM is formed by three processes: formation of non-volatile particles inside the combustor, the development of independent volatile particles downstream of the engine exit plane sourced to gaseous precursors, and the emission of heavy hydrocarbons from either incomplete combustion or lubrication oil. The latter may be emitted in gaseous form and later condense as liquid particles or as liquid on solid particles, or they may be emitted directly as liquids under some circumstances.

Non-volatile PM, often referred to as soot, is formed due to incomplete combustion that results in small amounts of carbonaceous particles in the exhaust. Volatile particles can be formed through condensation onto existing non-volatile particles as well as nucleation in which new particles are formed directly from gas phase precursors. Aircraft vPM is sourced to several emitted species including oxides of sulfur and nitrogen and hydrocarbons. Engine oil can also lead to vPM emissions.

The size distribution of aircraft engine particles is influenced by numerous factors including engine technology and throttle setting. Older engines tend to emit larger particles and particles tend to coagulate at higher thrust setting, resulting in larger particles (Kugele, Jelinek, & Gaffal, 2005). All aircraft PM is less that 2.5 μm (classified as $PM_{2.5}$). Figure 6 depicts the size distribution of aircraft PM from four engine types typical for Boeing 737-type commercial aircraft. The curve shows the progression from 7% power (Blue) to 85% power (Red) (Lobo, Hagen, & Whitefield, 2006).

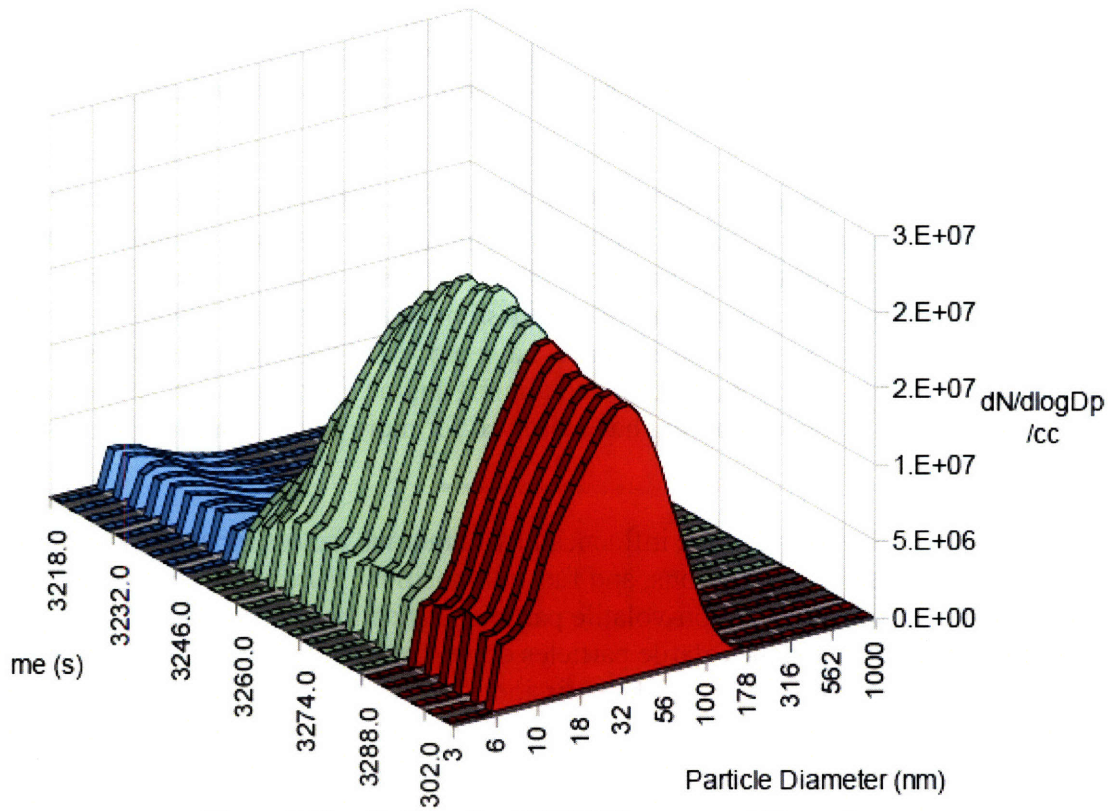

Figure 6. Results from the APEX2 Measurement Campaign

While there are currently no uniformly accepted methods for measuring aviation PM, the International Civil Aviation Organization (ICAO) has established standards for estimating engine smoke and the ICAO Committee on Aviation and Environmental Protection (CAEP) has recently accepted methods for estimating aviation PM.

ICAO defines engine smoke as the carbonaceous material in the exhaust emissions which obscure the transmission of light. Manufacturers of aircraft engines after 1986 are required to test engine exhaust to comply with ICAO standard in compliance with Annex 16 to the Convention on International Civil Aviation. For aircraft engine certification, tests must be performed at sufficient power settings to determine gaseous and smoke emissions. Operations are simulated using representative thrust settings and time in modes (*ICAO Annex 16*, 1993). Table 1 contains the time in mode and thrust setting assumption used for ICAO certification.

Operating Mode	Thrust Setting	Time in Mode
Take Off	**100%**	**0.7 min**
Climb Out (to 3,000 ft)	**85%**	**2.2 min**
Approach & Landing	**30%**	**4.0 min**
Taxi/Ground Idle	**7%**	**26.0 min**

Table 1. ICAO Time in Mode and Thrust Setting Assumptions

Pursuant with ICAO standards engine exhaust is characterized by a measure called *smoke number* (SN). Smoke Number, a dimensionless term that quantifies smoke emissions, is obtained by placing a probe in front of the engine exhaust nozzle and transferring the exhaust by sampling line to a filter. The filter is analyzed before and after the test using a reflectometer, an instrument to measure reflection density and the smoke number is determined by calculating the change in reflectance. The unitless Smoke Number (SN) for a particular mode is given by:

$SN = 100 (1-R_s/R_w)$

Where

- R_s is the reflectance of the stained filter and
- R_w is the absolute reflectance of clean filter material

Figure 7 shows the smoke analysis system.

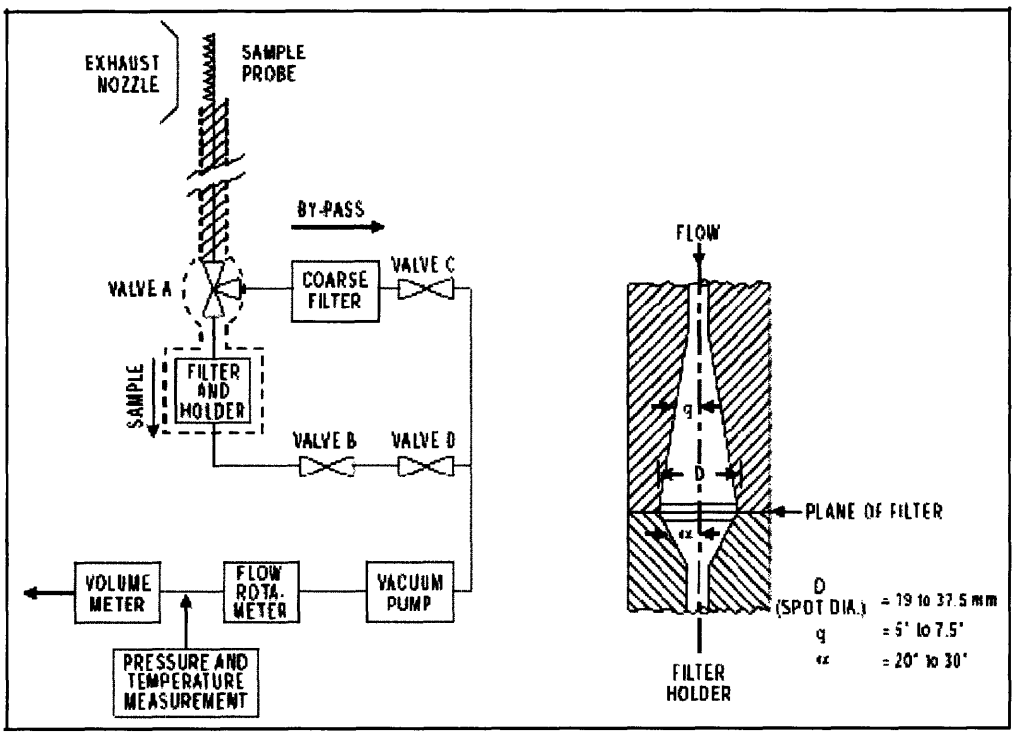

Figure 7. Smoke Analysis System ***(ICAO Annex 16, 1993)***

Smoke numbers for over 240 engines are contained in the ICAO Engine Exhaust Emission Data Bank. The database does not contain smoke numbers for all engines for all modes of operation. Many engines contain only contain the maximum smoke number. Approximately 97.5% of listed engines have maximum smoke numbers while only 28.8% listed have a complete set for all modes (Kugele et al., 2005).

Despite the lack of explicit PM metrics, efforts have been made to model PM emissions based on easily obtained information. Four broad categories of PM estimation methodologies have been used: (Wayson, Fleming, Kim, & Draper)

- *Simple Factor* Method: Multiplying the number of Landing/Takeoffs by a single factor
- *Compound Factor* Method: Multiplying the rate of fuel flow by a compound factor based on engine characteristics such as comparison of aircraft SN, thrust, operating pressure and/or temperatures
- *Grab Samples* and/or *Nearby Deposition* Methods: Estimating specific emissions rates for specific aircraft type or facility based on sample measurements and using simple rollback models to predict changes
- *Measured Mass* Method: Using actual measured mass test results for representative jet engines

To account for the various factors that influence aircraft engine PM and to represent the variety of engines flying today, the compound factor method is often employed because it establishes the relationships between smoke number and fuel flow values to PM emissions for a given operation. FAA and other agencies obligated under the current environmental regulations to evaluate the environmental impacts of aircraft PM employ a compound factor approach to estimate various components of total PM in the face of limited data.

Volatile PM is more difficult to estimate because it results from a number of complex chemical reactions and has no direct correlation to smoke number. For volatile PM estimates, grab and sample techniques and measured mass test results become increasingly important.

The following section will describe how the U.S. Federal Aviation Administration and researchers in industry and academia have approached the task of estimating total PM from aircraft by delineating the development and subsequent improvements of the First Order Approximation (FOA) method and the MIT PM Estimation method.

3.1.2 First Order Approximation (FOA)

The First Order Approximation has been developed by internal FAA processes and does not reflect the work of MIT. On April 11 -13, 2007, John Kinsey (EPA ORD) and Roger Wayson (FAA Volpe) developed a PM estimation methodology based on FOA3 specifically for the purposes of the Energy Policy Act. However, this section only details the preliminary work done with an unmodified FOA3.

FOA1 and FOA2

Recognizing the need for scientifically-based aircraft PM estimation techniques, the Federal Aviation Administration's Office of Environment developed a methodology to approximate PM emissions from aircraft called the First Order Approximation (FOA). Version 1.0 of FOA (FOA1) estimated only nvPM and integrated the work of Champagne, Whyte, and Hurley to determine a correlation between smoke number and

PM mass emissions (Champagne, 1971; Hurley, 1993; Whyte, 1982). A derived trend line based on the data from all three studies provided the starting point for FOA.

FOA1 relates the nvPM emission rates (ER) [in units of mg per second] to smoke number (SN) and fuel flow (FF) with the following equation:

FOA1 Equation: $$nvPM\_ER\left[\frac{mg}{\sec}\right] = 0.6SN^{1.8}FF$$

Where:

- FF is the ICAO fuel flow by mode per certified engine type (kilograms of fuel per second)

The calculated emission rate per mode is then multiplied by the respective time in mode (TIM) pertaining to one of the four certification thrust settings listed in Table 1. This calculation is repeated for the other modes of operation and then added together to get total nvPM for an LTO cycle of an engine and then multiplied by the number of engines per aircraft.

The problem of missing modal smoke numbers in the ICAO Engine Emissions Certification Databank was overcome by FOA1 by using maximum smoke numbers when estimates for other modes are not available.

FOA1 was released in 2003 and underwent peer review by a group of 70 experts, including members of the EPA. During the peer review process, the EPA and others recognized the most significant area of necessary refinement was the estimation of the proportion of volatile PM mass to non-volatile PM mass.
(*Status Report on Proposed Methodology to Characterize Jet/Gas Turbine Engine PM Emissions*, 2003).

FOA2 was released in 2005 and included total PM estimates based on simple scaling factors to accommodate for both non-volatile and volatile PM components. Limited data required a simple scaling factor was determined by three sources:

- A series of data reports from the U.S. Navy's Aircraft Environmental Support Office that approximated a 2:1 ratio for volatile to non-volatile components of PM (*Summary Table of Gaseous and Particulate Emissions from Aircraft Engines*, 1990)
- Preliminary EPA results from an unpublished study affiliated with NASA's Aircraft Particle Emissions Experiment (APEX1) campaign that estimated the ratio as closer to 3:1
- A theoretical paper produced by researchers at the Massachusetts Institute of Technology (MIT) that also implied a 2:1 ratio (Lukachko, Waitz, Miake-Lye, & Brown, 2005)

(Iovinelli, 2007)

While non-volatile PM emissions are estimated exactly as in FOA1, FOA2 used a conservative 3:1 ratio estimate that established a functional total PM estimate for jet-turbine aircraft. Due to the limited number of field measurements, the multiplier was given a 33% margin (Iovinelli, 2007).

FOA2 related total PM emission rates (ER) to smoke number (SN) and fuel flow (FF) with the following equation:

FOA2 Equation: $$PM_{TOTAL}ER\left[\frac{mg}{\sec}\right] = 2.4SN^{1.8}FF$$

Where:

- FF=the ICAO fuel flow by mode per certified engine type (kilograms per second)

FOA2 rests in the assumption that the volatile fraction of PM is directly related to the non-volatile fraction, and this is not supported by analyses of the microphysics of vPM formation (Lukachko et al., 2005). Still, FOA2 was the best available model at the time and was therefore incorporated into EDMS version 4.3 with a qualifier from EPA and FAA. A few specifics were noted in the qualifier including:

- For some engines a maximum smoke number is conservatively used because modal specifics are not available.
- Due to the uncertainties associated with limited data, the volatile portion includes an additional margin to be conservative.
- The accuracy of EDMS will be improved as future field measurements and scientific advances become available, and
- FOA is only applicable to aircraft that have ICAO smoke numbers.

(Iovinelli, 2007)

In June 2005, the FAA presented FOA2 to the technical emission group within ICAO's Committee on Aviation Environmental Protection (CAEP), Working Group 3 (WG3). Recognizing the need for a predictive PM methodology for commercial aircraft that is based on the evolving state-of-the-science, WG3 created the PM Ad-Hoc Group to redevelop the FOA methodology with an improved scientific foundation. The PM Ad-Hoc group was chaired by Ralph Iovinelli of the FAA and was composed of members from industry, academia, and government. What resulted was CAEP's FOA version 3.0 (FOA3).

FOA3

FOA3 estimates total PM by breaking PM contributors into various components, thereby decoupling the empirical relationship between FOA2's nvPM and vPM. Instead, nvPM is estimated separately from vPM, and vPM estimates are broken into 3 components. FOA3 uses the following general equations:

- Total vPM = vPM from Fuel Sulfur + vPM from Fuel Organics + vPM from Lubrication Oil
- nvPM = Based on smoke number to mass relationship
- Total PM = Volatile PM + Non-volatile PM

FOA3 is comprised of a suite of equations based on readily available data (such as smoke number and fuel sulfur content). Notable improvements over FOA2 include:

- Revised approximation between smoke number and non-volatile PM
- Mode-specific PM approximations to reflect different operational aspects of commercial jet engines
- Volatile PM approximations in terms of the individual chemical drivers

(*CAEP Information Paper 6*, 2007)

FOA3 Non-Volatile PM

FOA3 calculates nvPM using the ICAO smoke number; however, unlike previous FOA versions, the trend lines are more statistically defined with the use of multiple equations. Improved trend lines separate smoke numbers under 30 (generally newer modern engines) based on a series of laboratory experiments at QinetiQ (Hurley, 2005), from those over 30 (generally older engines still flying today). Hurley generated laboratory experimental data to develop a relationship between concentration index (CI), the mass of PM per unit of exhaust, and smoke number.

To account for missing modal smoke numbers, WG3's PM Ad-Hoc group accepted a method proposed by John Calvert of QinetiQ (Calvert, 2006). Calvert suggested that modal smoke numbers be estimated considering engine technology and quality of SN data. Instead of using maximum smoke numbers when all modes were not present, Calvert's method requires multiplying maximum numbers by a factor based on trends in SN. This method disaggregates by engine types such as Avaidgatel, Textron Lycoming, and GE CF34, and also by technologies such as double annular combustors (DAC). Maximum smoke numbers are multiplied by a derived factor to account for different modes of operation. Table 2 lists the multipliers used to adjust maximum ICAO smoke numbers.

	T/O	C/O	Approach	Idle
Most non-DAC cases	1.0	0.9	0.3	0.3
Aviadgatel cases	1.0	1.0	0.8	0.3
GE CF34 cases	1.0	0.4	0.3	0.3
Textron Lycoming cases	1.0	1.0	0.6	0.3
DAC cases	0.3	0.3	0.3	1.0

Table 2. Calvert Factors used to adjust maximum ICAO smoke numbers (*CAEP Information Paper 6*, 2007)

WG3's PM Ad-Hoc group acknowledged that smoke number measurements can have uncertainties as great as ± 3 due to differences in analysts and tests (*CAEP Information Paper 6*, 2007). PM emissions estimates that use the average estimate are known as the *best estimates.* The upper limit, obtained by adding 3 to the average estimate, are referred to by CAEP as *conservative estimates* not in the sense of an alternative way to calculate inflated estimates of nvPM, but rather in a sense of bounding the relationship between CI and SN.

The derived correlation between smoke number (SN) and nvPM concentration index (CI), the mass per volume of exhaust (mg/M^3), is represented using the following equations. For SN less than 30:

- Best Estimate:

$$CI = 0.0694SN^{1.23357}$$

- Conservative Estimate:

$$CI = 0.0012SN^2 + 0.1312SN + 0.2255$$

For SN greater than 30, a different regression analysis yields:

- Best Estimate:

$$CI = 0.0297SN^2 - 1.802SN + 31.94$$

- Conservative Estimate:

$$CI = 0.0297SN^2 - 1.6238SN + 26.801$$

To calculate the exhaust volumetric core flow rate (Q_{core}), a calculation based on the work of Eyers that takes into account the air-to-fuel ratio (AFR) by power setting (Eyers, 2005):

$$Q_{core} = 0.776AFR + 0.733$$

Where:

- Air-to-fuel ratios (AFR) are given as (Eyers, 2005):

Idle (7%): 106
Approach (30%): 83
Climbout (85%): 51
Takeoff (100): 45

For SN values measured under mixed flow conditions, the core flow rate (Q_{core}) is given by (Eyers, 2005):

$$Q_{core} = 0.776AFR(1 + BPR) + 0.877$$

Where:

- BPR is the bypass ratio as supplied in the ICAO Engine Emissions Certification Databank

This equation should also be used if it is not certain whether SN measurements were made under core flow or mixed flow conditions.

EI's can then be calculated with the common continuity equation:
EI=Q x CI
Where:

- EI=nvPM Emissions Index (mg/kg fuel)
- Q is the flowrate (m^3/kg fuel)
- CI is the concentration index (mg/M^3)

Based on the above derivation, the volumetric flow rates by mode are given in Table 3.

Mode	Volumetric core Flow Rate	Volumetric Flow Rate with Bypass Ratio
Idle	83.0	83.13 + 106(B)
Approach	65.1	65.29 + 83(B)
Climb-Out	40.3	40.45 + 51(B)
Take Off	35.7	35.80 + 45(B)

Table 3. Engine Volumetric Flow Rates by Mode (*CAEP Information Paper 6, 2007)*

FOA 3 Volatile PM

FOA3 accounts for volatile PM sourced to three components: fuel sulfur content, most of which is emitted as SO_2 and converted to sulfuric acid (H_2SO_4), fuel organics (hydrocarbon emissions or partially oxidized fuel), and lubrication oil.

PM from Sulfur

Sulfur emissions are assumed to be primarily a function of the amount of sulfur in the fuel and the conversion efficiency from elemental sulfur (S^{IV}) to sulfuric acid (S^{VI}). Sulfuric acid arises when fuel sulfur, most of which is emitted as SO_2, is oxidized. A molecular weight of 96 is assumed for sulfates and the volatile PM emissions index (EI) becomes:

$$EI = 1\times 10^{6}\left(\frac{FSC(\varepsilon)MW_{out}}{MW_{s}}\right)$$

Where:

- FSC=fuel sulfur content (%)

- ε=Elemental Sulfur to sulfuric acid conversion rate (%)
- MW_{out}=96 (Sulfate in the exhaust)
- MW_s=32 (Sulfur)

Fuel sulfur content is assumed to be between 0.046% to 0.068% of the total weight based on studies by the Intergovernmental Panel on Climate Change (IPCC) and Coordinating Research Council (CRC) (*Handbook of Aviation Fuel Properties, Third Edition*, 2004; 1999).

FOA3 uses a sulfur to sulfuric acid conversion efficiency based on the results of the SULFUR 1-7 experimental campaign (Schumann et al., 2001). The best estimate (average) is given as 0.5% conversion, while a conservative estimate (high) is given by 3.3%.

vPM from Organics

Volatile PM sourced to organics is based on results from the APEX1 measurement campaign in which the organic fraction of PM was separated from total PM by in-situ engine measurements (Wey et al., 2006). The results for the APEX1 measurement campaign are shown in figure 8. These results are based on only one engine, the CFM56-2-C1, with hopes of future improvements to account for a wider range. Figure 8 shows the PM trends estimated from the APEX1 campaign results. Two methods are available for calculating volatile PM contribution from organics.

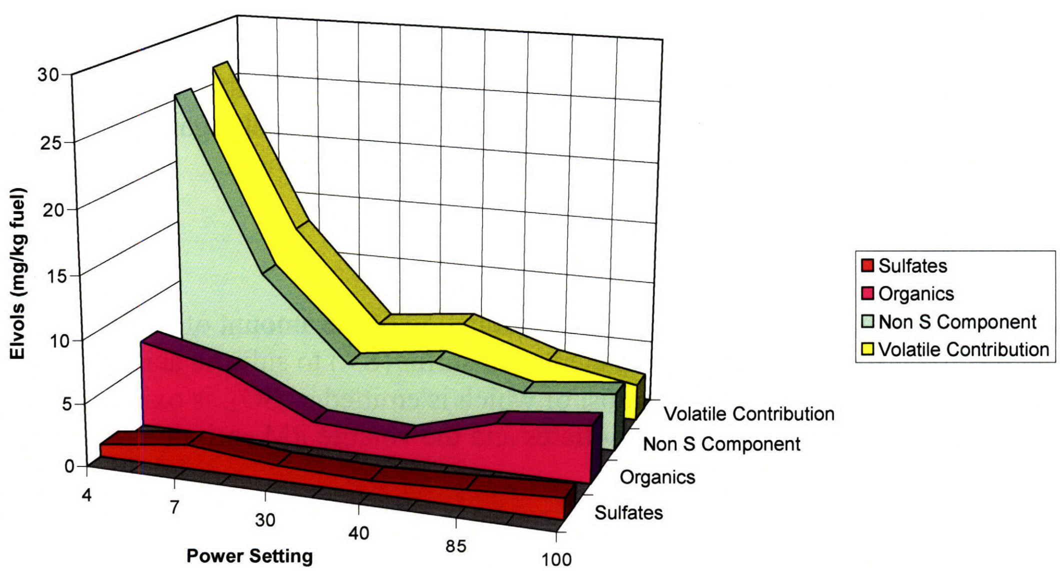

Figure 8. PM trends from APEX1 Measurements for a CFM56-2-C1 engine

Method 1:

Subtracting the sulfate component from total volatile contribution, results in the derived curve labeled Non S Component in Figure 8. However for 85% power and 100% power this is less than the total organic component. The reported value for the organic component was used for these higher thrust settings. The resulting Non S Component is assumed to be the organic fraction of the volatile particular matter (vPM) emissions, and can be used to determine the organic fraction for other engines in the ICAO Engine Emissions Certification Databank. Mode-specific emission indices for organics ($EI_{organics}$) can be obtained by emissions indices sourced to hydrocarbons (EI_{HC}) for addition engines with the following equation:

$$EI_{Organics} = \delta EI_{HC}$$

Where:

$$\delta = \left(\frac{V_{component}}{EI_{HC(CFM\,56-2-CI)}} \right)$$

Where:

- $V_{component}$ is the ratio based on the trend shown in figure #.
- $EI_{HC(CFM\ 56\text{-}2\text{-}CI)}$ is mode specific HC EI for CFM56-2-CI engine.

Mode specific values of δ are contained in Table 4.

Mode	δ
Take off	115
Climb out	84
Approach	56.25
Idle	6.17

Table 4. Mode specific values of HC EI multiplier

Method 2:
A second method involves applying the $V_{component}$ across the entire LTO cycle. This yields a multiplier of 85% to calculate the PM from fuel organics for the engine of concern. PM mass from organics ($PM_{Organics}$) becomes:

$$PM_{Organics}(grams) = (0.0085) \times (Total\ LTO\ HC\ Emissions)$$

PM from Lubrication Oil

Lubrication oil is assumed to have an effect on volatile PM formation; however, a direct link is yet to be established. It is assumed that this influence is captured in the PM measurements sourced to organics, but work is still ongoing to further investigate this relationship.

The FOA3 methodology is to be continually updated as scientific knowledge advances and more data becomes available. The next section describes another PM estimation method examined for the Energy Policy Act Study.

3.1.3 MIT PM Estimation Method

Another method for estimating aircraft PM was developed at the Massachusetts Institute of Technology (MIT), hereafter referred to as the MIT PM Estimation Method (MIT Method). The MIT Method is based on a theoretical paper by Stephen Lukachko and Ian Waitz of the Massachusetts Institute of Technology and Richard Miake-Lye and Robert Brown of Aerodyne Research, Inc (Lukachko et al., 2005). The paper addressed the response of trace chemistry in the temporal and spatial evolution of temperature and pressure along the entire intra-engine path by examining engine design and operational impacts on PM precursors of SO_X.

The MIT Method's also places an emphasis on PM formation as a result of engine parameters and requires other inputs for various engine combustor conditions. These conditions are obtained from a number of sources based on various assumptions:

- Kerosene heating values are estimated by assuming a uniformly distributed range between 42.9 and 48.2, the upper heating values derived from fuel standards.
- Reference values for pressure and temperature specification are based on 8 representative engine types separated by class (thrust) shown in Table 5.

	Class (kN)	<100		100-200		200-400		>400	
	Thrust (kN)	60	65	100	170	205	230	250	420
Take Off	P_3 (atm)	16	15	23	25	20	27	27	37
	T_4 (K)	1350	1200	1520	1510	1400	1560	1540	1940
Climb	P_3 (atm)	14	12	19	22	17	24	23	31
	T_4 (K)	1300	1140	1440	1450	1340	1510	1480	1840
Cruise	P_3 (atm)	6.0	5.7	8.0	9.0	7.1	7.3	9.7	13
	T_4 (K)	1170	1030	1340	1340	1270	1210	1370	1710
Approach	P_3 (atm)	6.0	5.7	7.1	9.2	7.6	10	9.8	13
	T_4 (K)	960	870	1010	1080	1010	1140	1110	1440
Idle	P_3 (atm)	2.6	2.6	3.3	3.7	3.3	4.4	4.0	5.3
	T_4 (K)	750	710	840	870	830	940	900	1220

Table 5. Cycle Parameter Specification for 8 Representative engine types (Lukachko et al., 2005)

To account for diversity in the U.S. fleet, the MIT Method maps all aircraft in the U.S. fleet to 19 representative aircraft types, 16 large and 3 regional, based use in the commercial aviation market.

MIT Method Non Volatile PM

Engine smoke numbers are obtained from the ICAO engine emissions database and are used to calculate nvPM. If a complete set of smoke numbers are not available, the present numbers are averaged. If there are missing smoke numbers, an average of the available ones are used to represent all four modes. If no data exists, an average of the ICAO-given range is used. If no range is given, the maximum smoke number is used.

A random error is applied to calculated smoke number to represent the engine-to-engine variability in SN for new production. The smoke number for each mode is given a normally distributed (standard deviation: σ=17%) random value to account for any measurement error.

The MIT method derives a correlation between smoke number (SN) and PM mass concentration (MC) based on the work of Hurley, Champagne, Whyte, and Hall et al. (Champagne, 1971; Hall, Stouffer, & Colket, 2004; Hurley, 1993; Whyte, 1982). The MIT model makes a random choice among SN Correlations. A random error (σ=20%) is assigned to the mass concentration calculated to account for International Panel on Climate Change (IPCC) finding that up to a 20% exists between different correlations (Penner, Lister, Griggs, Dokken, & McFarland, 1999).

An altitude correction is also made. Smoke number measurements are made at sea level static (SLS) conditions and neglect the effect that altitude has on PM formation. The soot concentration at altitude (C_{soot}) is given by (Dopelheuer & Lecht, 1999):

$$C_{Soot} = C_{Soot,\mathrm{Ref}} \left(\frac{\Phi}{\Phi_{\mathrm{Ref}}} \right)^{2.5} \left(\frac{p_3}{p_{3,\mathrm{Ref}}} \right)^{1.35} \frac{e^{-20000/T_3}}{e^{-20000/T_{3,\mathrm{Ref}}}}$$

Where:

- $C_{Soot,Ref}$ is the reference soot concentration at SLS
- Φ is the equivalence ratio
- p_3 is the combustor inlet pressure, and
- T_3 is the combustor inlet temperature

Emission indices are calculated, taking into account the exit temperature.

$$EI = \frac{C}{100} \cdot R \cdot \frac{T_{amb}}{P_{amb}} \cdot \left(\frac{1}{FAR} + 1\right)$$

Where:

- C is the soot particle density
- R is the universal gas constant
- T_{amb} is the atmospheric temperature at altitude.
- P_{amb} is the atmospheric pressure at altitude , and
- FAR is the fuel to air ratio

The equivalence ratio is represented by a uniform random distribution between upper and lower estimates as given by Han (Han, 2003). A random error (σ=30%) is applied to the equivalence ratio based on laboratory and flame tests.

Volatile PM

Volatile PM is estimated by considering the chemical precursor science and microphysics of aircraft emission. At exhaust temperatures, SO_3 converts to volatile H_2SO_4 in the presence of water vapor. Nitrous acid (HONO) and nitric acid (HNO_3) have a smaller tendency to nucleate independently but may contribute to total volatile PM mass via uptake on existing particles. Although HNO_3 production is much less frequent that H_2SO_4, it can also play a role on PM formation in the plume. Still, the MIT Method estimates volatile PM with measured conversion efficiencies (ε) from aircraft emissions of SO_X to H_2SO_4.

Based on the thermodynamic conditions for 8 representative engines studied, the mean conversion efficiency was found to be 2.8% to 6.5% for sulfate precursors. This suggests emissions indices of 0.06-0.13 g/kg-fuel for a fuel sulfur content of 500 ppm.

The MIT Method does not include PM sourced to HC species based on the finding that thermodynamic conditions are not favorable to PM production from hydrocarbons. The MIT method does not estimate PM sourced to engine lubrication oil.

A complete description of the work of Lukachko, Waitz, Miake-Lye, and Brown can be found in Engine Design and Operational Impacts on Particulate Matter Precursor Emissions (Lukachko et al., 2005).

3.2 APU Usage

In addition to the challenges of estimating PM emissions, there are also challenges with estimating aviation APU usage. APU usage depends on a range of factors including aircraft size, weather, and aircraft carrier. Larger aircraft generally carry more passengers and are more likely to utilize on board APU's. Seasonal variations related to extreme weather condition may also make APU use necessary. Many carriers have standard operation procedures as to APU use. However, the ultimate decision rests with the pilot (Graham, Cointin, & Thompson, 2006).

One of the most important indicators in APU usage time is the availability of ground support equipment that can be used in place of the APU to heat or cool the cabin and provide ground based power. At least four factors must be considered:

- *Departure Preparation*: If ground based support is available APU's may be turned on just prior to push back from the gate or if no ground support is available the APU's may be started to help prepare the cabin for passengers or cargo.
- *Departure Taxi*: Once an aircraft leaves the gate the carrier may have a standard operating procedure to taxi on fewer than all engines. If the engines are not producing the needed power to maintain the cabin environment, the APU may used to supplement.
- *Arrival Taxi*: When the aircraft lands and taxis to the gate the APU again may be used to supplement power depending on the use of the aircraft's engines.
- *Arrival to the Gate*: If power and conditioned air are available at the airport's gate the APU might remain on until the aircraft is properly connected to the ground source. If no ground support is available the APU shutoff or remain operating depending on when the aircraft will be used next or for maintenance purposes.

(Graham et al., 2006)

These results of the survey of APU usage that included several carriers were integrated into EDMS for more accurate characterization of APU emissions. Because of the variety of data gathered for the study, a range of values was considered depending on the size of the aircraft and the ground support available at the airport. Figure 9 illustrates the relationship between APU usage and airport facilities. Airports with high access to ground support require fewer minutes of APU usage, while those with low access require longer times. Wide body aircraft require longer APU usage time than narrow body aircraft and wide body aircraft greater fluctuation in usage time.

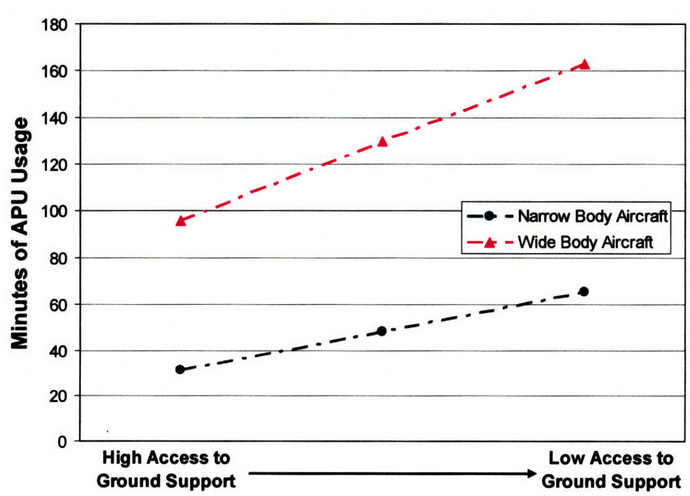

Figure 9. Minutes of APU usage versus airport facility

3.3 Baseline Inventory for Aircraft in Nonattainment Areas

Using the FOA3 *best estimate* to predict $PM_{2.5}$ emissions and a medium APU use assumption obtained from the Metron survey, CSSI generated a baseline inventory for airports in nonattainment areas. Only emissions under 3,000 feet were generated to account for Takeoff and Climbout, Approach and Landing, and Taxi and Ground Idle emissions. Using a conservative approach, all aircraft were assumed to taxi out on all engines from pushback to wheels up.[3]

The FAA's Voluntary Airports Low Emission (VALE) program identifies 150 airports currently located in $PM_{2.5}$, Ozone and/or CO nonattainment areas. Two of the 150 airports, Block Island Airport in Rhode Island and Lake Hood Airport in Alaska, had only limited operations data and therefore were dropped from this analysis. The remaining 148 airports serve as the base for our analysis on commercial aviation's contribution to county inventories of criteria pollutants.

CSSI processed Instrumental Flight Rules (IFR) traffic first. All IFR traffic was derived from the FAA Enhanced Management System (ETMS). ETMS provide the flight number, origin and destination information, and generic aircraft type. The Bureau of Transportation Statistic's (BTS) On Time Performance database was used to match flight numbers to aircraft registration number to relate each flight to a specific aircraft type, as well as taxi times. If flights are not accounted for in the BTS database, they are assumed to have taxi times equal to the average of reporting for flights for similar operations during the same hour. Registration information for a particular aircraft was obtained from the FAA's aircraft registration database or BACK Aviations fleet database. Registration information provides engine/aircraft pairing. The FAA Aviation Environmental Design Tool (AEDT) was used to determine the trip length and an associated estimate for aircraft weight. (Ohsfeldt et al., 2007)

Some visual flight rules (VFR) traffic does not appear in the ETMS database, so total VFR operations were obtained by subtracting all IFR operations from the total airport operations provided by the Air Traffic Activity Data (ATADS). VFR operations were assumed to operate at the maximum weight. (Ohsfeldt et al., 2007)

All aircraft operations were then aggregated by airframe, engine and takeoff weight to ease the computational requirements of EDMS. Taxi times were averaged across all operations.

The resulting inventory contains total emissions of CO, NO_X, SO_X, VOC, and $PM_{2.5}$ for aircraft emissions from 148 airports in nonattainment areas. There is great range in total airport emissions reflecting the large range of total operations from a given airport in a nonattainment area.

---

[3] The Energy Policy Act Study will also include a Realistic Performance Scenario in which alternative taxi out assumptions are investigated.

3.3.1 Baseline Inventory v. National Emissions Inventory Comparison

Assessing the relative contribution of aircraft requires the use of total county emissions inventory data. To assess the magnitude aviation's contribution, the following section provides a comparison of aircraft emissions with the EPA data for all sources.

The EPA estimates county-level emissions for all criteria air pollutants every three years in the National Emissions Inventory (NEI). The database includes information on sources that emit criteria pollutants and their precursors as well as those emissions designated as hazardous pollutants. The database includes annual estimates of point, non-point, and mobile source emissions in all 50 states as well as the District of Columbia, Puerto Rico, and the Virgin Islands. EPA collects data from a number of sources including:

- Emissions inventories compiled by state and local environmental agencies
- Databases related to EPA's Maximum Achievable Control Technology (MACT) programs
- Toxic Release Inventory (TRI) data
- EPA's Emissions Tracking System/Continuous Emissions Monitoring data (ETS/CEM) and the Department of Energy fuel use data
- Federal Highway Administration for miles traveled estimates and emissions factors from EPA's MOBILE, a computer model that estimates emissions from cars trucks, and motorcycles
- EPA's NONROAD computer model to estimate emissions from nonroad engines equipment and vehicles emissions
- Previous emissions inventories if current data is unavailable

(*About the National Emission Inventory Database*, 2007)

NEI version 2.0 for 2002 was used to estimate emissions from point, non-point, and mobile sector sources, and default estimates generated by BEIS3.12 were used to account for biogenic emissions from soils and vegetation.[4]

The 148 airports are located in 134 counties. There are 8 counties that contain two commercial airports and 3 that contain three commercial airports. Aircraft contribution to county budgets of primary pollutants ranged from less than .01% to as high as 36.36% with an average contribution of 0.82%. Average contributions of 0.67% for VOC's, 0.81% for CO, and 0.24% for $PM_{2.5}$ were found. Aircraft do not emit particles over 2.5 μm, so contributions to PM_{10} county budgets are the lowest, ranging from less than .01% to 1.34% with a mean value of 0.07%. NOx contributions were as high as at 26.28% with an average value of 1.73%. SOx contributions were as high as 36.36% with an average contribution of 1.39%. The results for all pollutants for all 134 counties are shown in Figure 10.

[4] Biogenic Emissions were not estimated for Alaskan counties.

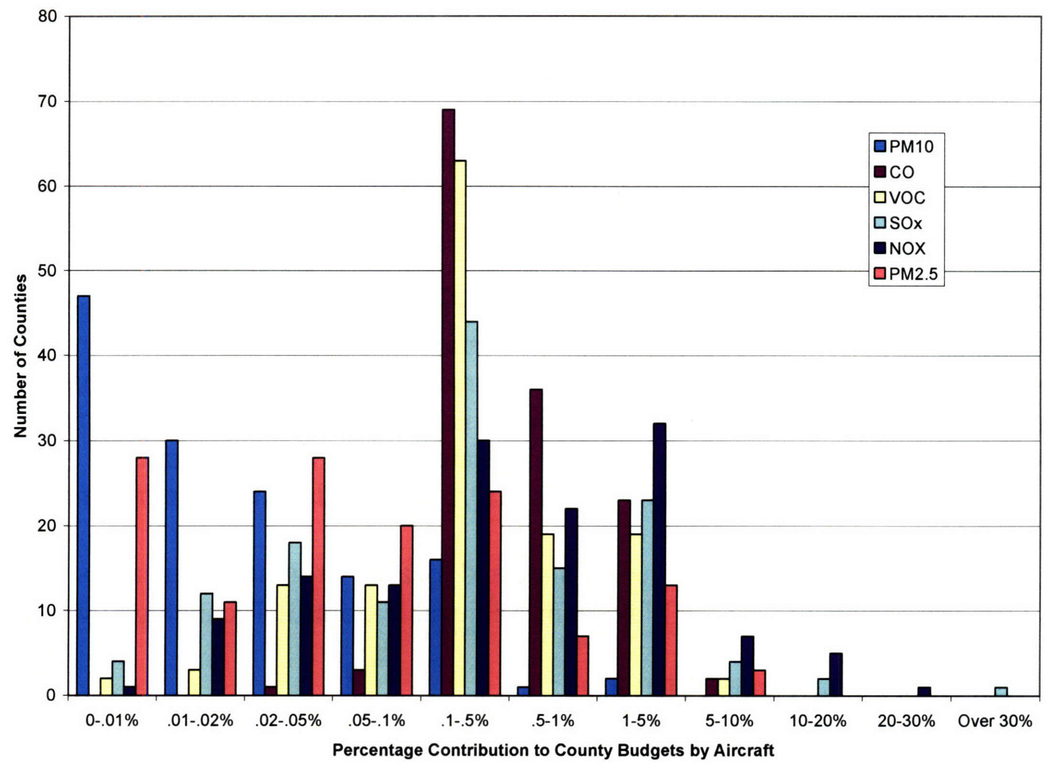

Figure 10. Percentage Contribution to County Budgets of Primary Pollutants by Aircraft (2002)

A complete list of airports and their relative contributions to county budgets can be found in Appendix D. Aircraft contributions by county can be found in Appendix E.

4.0 Effects of Aircraft Emissions on Public Health

Assessing the impact of aircraft emissions on county inventories of criteria pollutant precursors is a first order measure of aviations' influence on local air quality and a rough indicator of the need for control strategies. However, this metric is a poor measure of effects on public health because it does not account for the dispersion of these pollutants, the formation of secondary pollutants, or the population subsequently exposed.

Aircraft emissions are influenced by complex atmospheric chemistry and regional transport processes. Atmospheric modeling is necessary to simulate the dispersion of pollutants away from centers of aviation activity and to account for the chemical reactions that lead to the formation of secondary pollutants, such as ozone as well fine particulate matter species like ammonium sulfate and ammonium nitrate. Fine particulate matter ($PM_{2.5}$) and ozone are key public health concerns. Consistent with prior EPA analyses of criteria pollutants (e.g., Clean Air Interstate Rule), this analysis focuses on the health effects of these two pollutants.

This section presents an analysis of the preliminary air quality modeling done to predict changes in ambient concentrations of ozone and $PM_{2.5}$ and an analysis of the health effects that result from the removal of commercial aircraft emissions. This analysis adapts the three major components commonly employed by EPA when assessing the benefits and costs of pollution controls:

- Calculation of the impact of aircraft on U.S. emissions inventories of precursors to ozone and $PM_{2.5}$.
- Air quality modeling to determine changes in ambient concentrations of ozone and $PM_{2.5}$: a baseline scenario with all emissions and a control scenario in which commercial aircraft emissions have been removed.
- A health impact analysis to determine the change in human health and welfare resulting from the sensitivity case, both in terms of physical effects and monetary values that result.

This health impact analysis reflects work that is consistent with EPA regulatory impact analyses. The selection of endpoints, concentration response functions, aggregation and pooling methods, and valuation methods mirror EPA analyses, including the recent Regulatory Impact Analysis Locomotive and Marine Engine Rule (*Draft RIA Locomotive & Marine Rule*, 2007). Any changes in EPA methods have been noted and will be amended in the final benefit analysis for the Energy Policy Act Study.

4.1 Aircraft Impact on Regional Emissions Inventories: RPO Emissions Data

The emissions inputs for this benefit analysis were created by the University of North Carolina, Institute for the Environment and draw upon the work performed by UNC to prepare base case *modeling inputs for the Western Regional Air Partnership 2002 modeling (Tonnessen et al., 2006).*

While an inventory similar to the one created in Chapter 3 will be used as a more accurate aircraft inventory for the final Energy Policy Act Study, aircraft emissions were estimated using EPA Regional Planning Organization (RPO) data for this preliminary assessment. Emissions inventories can have a substantial impact on final health impact results. This point reaffirms the fact that these preliminary findings should be considered as examples to illustrate methods that will be used later with the more detailed inventories, rather than preliminary indicators of final results.

EPA-sponsored RPO's were created to address visibility impairment from a regional perspective. Because many pollutants that contribute to regional haze originate from sources outside of a particular state, RPO data are obtained by collaboration of the member states. RPO inventories include emissions from a variety of state and regional sources including aircraft.

There are five RPO established by the EPA shown in Figure 11:

- The Western Regional Air Partnership (WRAP)
- The Mid-Atlantic/Northeast Visibility Union (MANE-VU)
- Central Regional Air Planning Association (CENRAP)
- The Midwest Regional Planning Organization (MRPO)
- The Visibility Improvement-State and Tribal Associations of the Southeast (VISTAS)

Figure 11. Regional Planning Organizations (RPOs) (*Regional Planning Organization*, 2007)

RPO inventories for the year 2002 were used. UNC serves as emissions technical lead for one of the RPOs, i.e., the Western Regional Air Partnership (WRAP), and worked with other RPO and EPA to collect the data used to create the emissions inventory used in this analysis (Hanna, Arunachalam, Adelman, Baek, & Holland, 2006; Tonnessen et al., 2006).

Emissions data falls into six categories: stationary point, stationary area, on-road mobile, nonroad mobile, fires, and biogenic. Each of these categories contain characteristics, such as spatial information for locating the sources on the model grid, temporal activity patterns of emissions, and emissions estimates for various pollutants from sources within each category (Hanna et al., 2006).

For this analysis, 2002 RPO emissions estimates were processed through the Sparse Matrix Operator Kernel Emission (SMOKE). EPA RPO's and other agencies often provide emissions inventories as annual values (tons/year), and SMOKE processes these values into hourly, gridded, model-species-specific data to feed into air quality models. EPA SMOKE also contains the Biogenic Emissions Inventory System, version 3 (BEIS3) to estimate biogenic emissions from soils and vegetation as well as a driver for EPA's MOBILE6 model, which estimates emissions from on-road mobile sources.

All emission sources included in the RPO inventories were included for the base case CMAQ runs. For the sensitivity case, commercial aircraft emissions were removed using EPA Source Classification Codes (SCC). The SCC for commercial aircraft (2275020000) treated as a nonroad mobile source, was isolated and removed from all RPO inventories. Aircraft emissions for four states, Indiana, Michigan, Ohio, and Wisconsin, could not be located due to inconsistencies with the EPA SCC. These states had included aircraft emissions in the point source inventory instead of the default non-road emissions inventory. Emissions from Los Angeles International Airport (LAX) were identified in a different input file after the simulation had already begun due to similar inconsistencies, thus emissions from that airport were not removed. Still, the remaining airports represent a wide variety of commercial aviation activities and meteorological and geographical variability and were used for this preliminary analysis (Hanna et al., 2006).

The following section describes the modeling that was done using these emission inventories. For the base case as well as the sensitivity case UNC performed air quality modeling to predict changes in ambient concentrations of ozone and $PM_{2.5}$.

4.2 Air Quality Modeling

Preliminary air quality modeling was conducted by the University of North Carolina Institute for the Environment as part of an ongoing effort to derive statistical relationships between airport emissions and county-wide pollution levels (Hanna et al., 2006). The results of this analysis are used to provide a preliminary estimate, though the Energy Policy Act Study will include other air quality modeling results.

Primary pollutants are subject to transport processes and complex chemical pathways that affect concentration levels on a local and regional scale. Atmospheric residence times can extend for multiple days; therefore it is important to consider regional scales even when assessing aircraft emissions from distinct airport locations.

UNC performed a national scale air quality modeling analysis to estimate concentrations of ozone and $PM_{2.5}$ for two scenarios: a base case that includes all emissions and a sensitivity scenario in which all emission from commercial aviation have been removed. The two cases were analyzed using the EPA's Community Multi-Scale Air Quality (CMAQ) Modeling System (Byun & Ching, 1999), a three dimensional grid-based Eulerian air quality model designed to estimate the fate of ozone precursors, primary and secondary particulate matter concentrations and deposition over regional and urban scales. The CMAQ model is commonly used to demonstrate attainment of NAAQS by individual states for State Implementation Plans (SIP's), and for several national policy initiatives. The CMAQ model was peer-reviewed in 2003, and the latest version of CMAQ (Version 4.5) used for this analysis reflects improvements to a number of model components (Amar et al., 2004).

The CMAQ modeling domain includes all of the contiguous 48 states and portions of Canada and Mexico. The horizontal grid cells are approximately 36 km by 36 km and include vertical layers that reach approximately 16,200 meters in altitude.

The inputs to CMAQ include emissions from anthropogenic as well as biogenic sources, meteorological data, and initial boundary conditions. As described in the previous section, emissions estimates were derived from RPO inventories.

The CMAQ meteorological inputs were derived from the Mesoscale Model generation 5 (MM5). The MM5 solves a set of chemical and thermodynamics equations that govern atmospheric motion and was derived from a simulation of the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) (Grell, Dudhia, & Stauffer, 1994). UNC used version 3.6 over the entire continental United State at 36-km resolution. Initial values for the MM5 model were obtained from the National Center for Environmental Prediction (NCEP) Eta model as 40-km horizontal resolution (Hanna et al., 2006).

The preliminary assessment includes four months of modeling during the summer season, i.e. May-August 2002. While these four months account for close to an EPA-defined ozone season, all effects may not be captured by modeling only these months. PM concentrations peak during various times of the year depending on region, and all of the effects are not adequately captured by examining only the summer months. Moreover, there are additionally defined ozone seasons that typically follow state lines, and most states have a longer ozone season than EPA defines. In fact, only states like North Dakota have an ozone season matching EPA's. California's ozone season lasts the entire year. The larger EPACT Study will include a full year's worth of air quality modeling to fully capture the range of ozone and PM variations, whose concentration peak at different times of year depending on region. Figure 12 shows calculated ozone seasons by state.

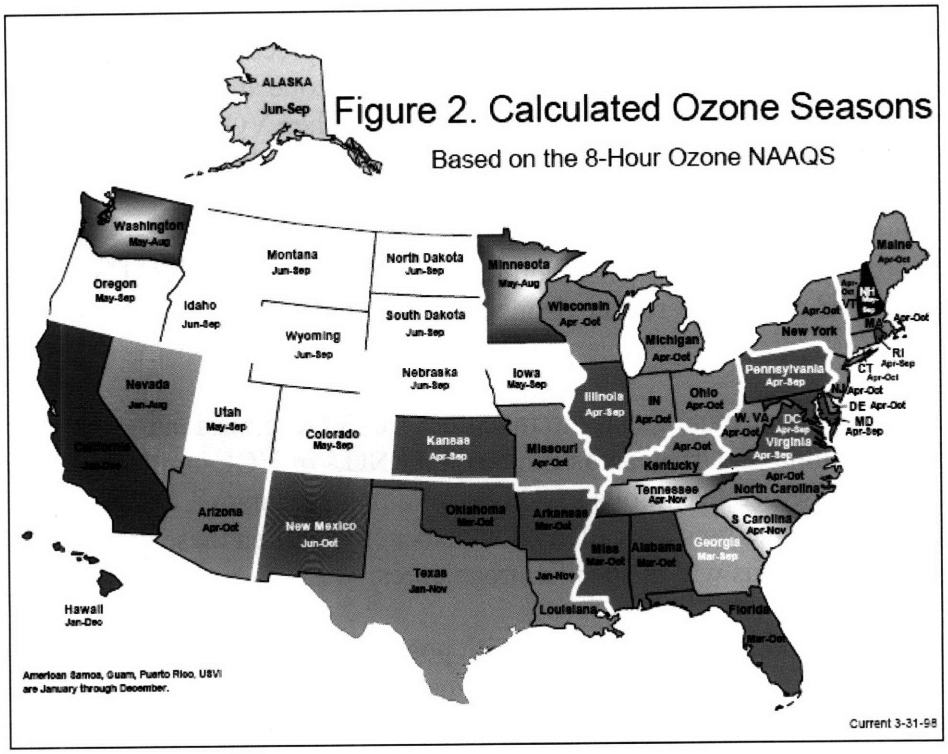

Figure 12. U.S. Ozone Seasons

Using the above inputs, CMAQ provides hourly concentrations of ozone and PM, in addition to various other pollutants. From these hourly values, daily average PM was calculated. The daily maximum 8 hour ozone concentration was calculated by running an 8 hour average starting at every hour (8 hours starting at 00GMT and then for 8 hours starting at 01 GMT, and so on). The daily averages for each case were averaged to calculate monthly and seasonal (May-August) values. The percent difference in concentration was calculated as:

- (Control Case-Base Case)/Base Case x 100

Thus, positive values denote a control case in which concentrations are higher than the base case (detriment to air quality) and negative values denote control case values that are lower that the base case (improvement in air quality).

The CMAQ modeling reveals large areas in which the removal of aircraft emissions results in decreases in ozone 8-hr average concentrations. However, there are also areas that result in an increase in ozone, or *ozone disbenefits*. Ozone disbenefits occur over large urban cores such as Atlanta, Chicago, and several areas of the northeast Corridor. The CMAQ model revealed as much as a 6.4% increase in ozone for localized areas resulting from the removal of aircraft emissions (Hanna et al., 2006).

The photochemical production of ozone is the result of complex atmospheric and chemical processes. Ozone formation is governed by two precursor pollutants: reactive volatile organic compounds (VOC's) and NO_X. The relationship between NO_X, VOC, and ozone is driven by complex, nonlinear photochemistry.

Ozone formation depends not only on the quantity of it precursors, but also on the ratio of the quantities of NO_X to VOC. The highest levels of ozone are produced when both VOC and NO_X emissions are present in abundance. When VOC levels are high, relatively small amounts of NO_X enable ozone to form rapidly. Under these conditions, NO_x reductions are effective at reducing ozone. Areas that meet these conditions are called *NO_X-limited.* When NO_X levels are relatively high and VOC levels are relatively low, NO_x foms little ozone. Such conditions are called *VOC-limited.* Under these conditions, VOC reductions reduce ozone formation, but reductions in NO_X can increase ozone.

Biogenic sources contribute greatly to inventories of VOC emissions, so rural areas are generally NO_x-limited. Urban areas can be either NO_x- or VOC-limited, or a mixture of both, in which case ozone exhibits sensitivity to either precursor. Ozone increases that result from NOx reductions are called NOx disbenefits. Often these disbenefits are limited to small regions within specific urban cores.

While ozone disbenefits are highlighted with positive contributions to ozone concentrations around some urban cores, almost all areas experience $PM_{2.5}$ reductions with the removal of aircraft emissions. Tables 6 and 7 summarize the CMAQ results for ozone and $PM_{2.5}$. Figure 13 and 14 show the percentage difference for the base and control case for 8-hour ozone and daily $PM_{2.5}$ respectively.

MAY	Daily Maximum 8h O_3 (ppb)			
	Base	Control	AbsDiff	PercDiff (%)
Min.:	22.3	22.6	-1.6	5.1
Mean:	48.2	48.3	-0.1	0.1
Max.:	65.3	65.3	0.1	-0.2
JUNE	**Daily Maximum 8h O_3 (ppb)**			
	Base	Control	AbsDiff	PercDiff (%)
Min.:	26.3	26.6	-2.8	5.2
Mean:	56.1	56.2	-0.1	0.1
Max.:	75.3	75.4	0.2	-0.3
JULY	**Daily Maximum 8h O_3 (ppb)**			
	Base	Control	AbsDiff	PercDiff (%)
Min.:	21.1	21.0	-3.3	5.9
Mean:	57.6	57.6	0.0	0.1
Max.:	86.9	87.0	1.0	-1.4
AUGUST	**Daily Maximum 8h O_3 (ppb)**			
	Base	Control	AbsDiff	PercDiff (%)
Min.:	24.9	25.4	-3.6	6.0
Mean:	55.7	55.7	-0.1	0.1
Max.:	84.4	84.3	0.3	-0.5

Table 6. CMAQ 8-hour Ozone Results Summary

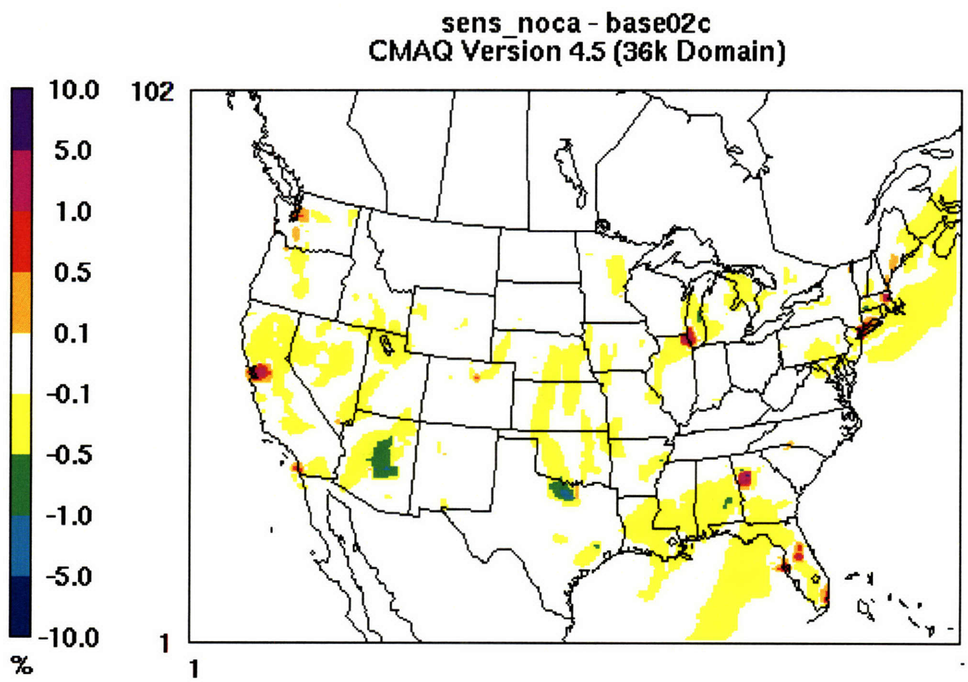

Figure 13. Percentage Difference in Maximum Daily 8 hour Ozone Measurements for the Control Scenario with Aircraft Emissions Removed

MAY	Daily Average $PM_{2.5}$ (ug/m3)			
	Base	Control	AbsDiff	PercDiff (%)
Min.:	1.7	1.7	0.0	0.1
Mean:	9.6	9.6	0.0	-0.3
Max.:	24.8	24.5	1.3	-8.4
JUNE	**Daily Average $PM_{2.5}$ (ug/m3)**			
	Base	Control	AbsDiff	PercDiff (%)
Min.:	2.7	2.7	0.0	0.0
Mean:	11.8	11.7	0.0	-0.3
Max.:	32.1	31.9	1.6	-9.8
JULY	**Daily Average $PM_{2.5}$ (ug/m3)**			
	Base	Control	AbsDiff	PercDiff (%)
Min.:	2.5	2.5	0.0	0.0
Mean:	12.0	11.9	0.0	-0.3
Max.:	31.8	31.8	1.7	-9.1
AUGUST	**Daily Average $PM_{2.5}$ (ug/m3)**			
	Base	Control	AbsDiff	PercDiff (%)
Min.:	2.8	2.8	0.0	0.0
Mean:	14.2	14.2	0.0	-0.2
Max.:	36.4	36.3	1.9	-9.4

Table 7. CMAQ Daily Average $PM_{2.5}$ Results Summary

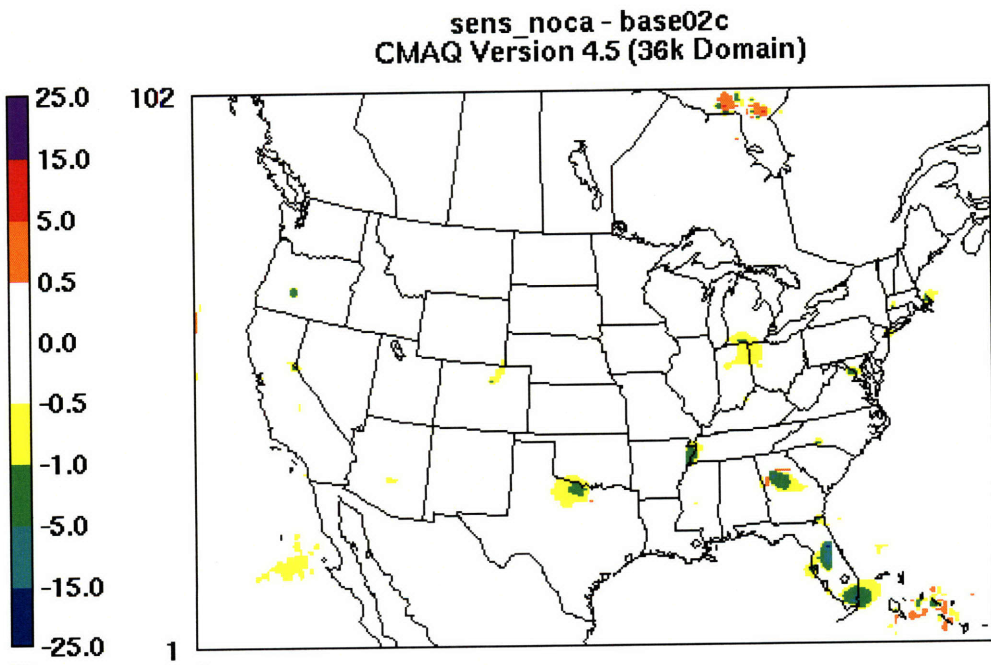

Figure 14. Percentage Difference in Maximum Daily $PM_{2.5}$ Measurements for the Control Scenario with Aircraft Emissions Removed.

4.2.1 Converting CMAQ Outputs for Benefit Analysis

Air quality modeling results were processed for use in the Environmental Benefits Mapping and Analysis Program (BenMAP), an EPA tool that combines air pollution monitor data, air quality modeling data, census data, and population projections to calculate a population's potential exposure to ambient air pollution. BenMAP is commonly employed by EPA to estimate the benefits associated with pollution reduction strategies (*BenMAP Fact Sheet*, 2004).

The following section describes how the CMAQ outputs generated by UNC were processed in BenMAP.

4.2.2 Ozone Processing in BenMAP

Population exposure is estimated in BenMAP using the Criteria Air Pollutant Modeling System (CAPMS), a population-based geographic information system for modeling changes in population exposure and estimating the associated health impacts. To forecast population exposure to ozone and PM, CAPMS uses air quality modeling results, EPA monitor data files, and data from the US census along with population projections (*Abt, Associates*, 2003).

CMAQ ozone model data is not used directly. Ozone model data is used only to scale monitor data. This is done using the Voronoi Neighbor Averaging (VNA) algorithm. The VNA algorithm works by identifying the set of air quality monitors that best "surround" the center of a population grid cell. Monitor data is then scaled with model data to generate air quality forecasts (*Abt, Associates*, 2003).

The advantage of model data is that it provides estimates in instances where monitor data is not available. Air quality monitors often miss a number of observations throughout the year. To account for missing days CAPMS represents the distribution of air quality levels with a discrete number of points or "bins." The number of bins equals the number of days analyzed, and each bin represents a certain range in a distribution. Missing days are assumed to have the same distribution as the available data (*Abt, Associates*, 2003).

Hourly model data for ozone were generated by day, sorted from low to high and then broken into deciles. A representative average value was assigned to each decile. Monitor data was then prepared in BenMAP by sorting values by concentration level and assigning the monitor data to one of the ten model data groups. (The monitor values in the lowest group are paired with the model data in the lowest group, and so on.)

BenMAP then uses VNA to identify the monitors surrounding each population grid cell, and then combines the representative model values and the ozone monitoring data to calculate the following (*Abt, Associates*, 2003):

$$adjusted\ monitor_{i,j,future} = monitor_{i,j,base} \cdot \frac{CMAQ_{j,k,future}}{CMAQ_{j,l,base}}$$

Where:
adjusted monitor = predicted hourly ozone level, after adjusted by model data (ppb)
monitor = observed hourly ozone level (ppb)
i = hourly identifier
j = model decile group
k = grid cell identifier
l = grid cell identifier for grid cell containing the monitor
base = base year
future = future year
CMAQ = representative model decile

After adjusting the monitor value, the appropriate concentration metric for estimating health effects is derived (e.g. Daily average). Using neighboring monitors for each grid cell, BenMAP calculates the inverse distance-weighted average of the monitor value (*Abt, Associates*, 2003):

$$population\ grid\ cell_{future} = \sum_{m=1}^{n} adjusted\ monitor_{m,future} \cdot weight_{m}$$

Where:
population grid cell = inverse distance-weighted ozone metric at population grid (ppb)
adjusted monitor = predicted ozone metric, adjusted by model data (ppb)
m = monitor identifier
future = future year
weight = inverse distance weight from monitor

Lastly, BenMAP takes the difference between baseline and control scenario for each "bin." For each grid cell we get bins that represent the difference between the baseline and control scenario, and these values are used to estimate the change in incidences of adverse health effects.

More information on ozone model data processing in BenMAP can be found in Chapter 2 of the Preliminary Nonroad Landbased Diesel Engine Rule (*Abt, Associates*, 2003).

4.2.3 PM Processing in BenMAP: Speciated Modeled Attainment Test (SMAT)

Changes in $PM_{2.5}$ concentrations for each 36 km by 36 km grid cell were estimated from CMAQ air quality modeling data only. For each grid cell the annual mean (calculated from just four months of model data) was used to represent changes in ozone concentrations.

However, this is not consistent with EPA benefit analyses.

To determine the health impacts of PM for use in benefit analyses, the EPA uses model predictions in conjunction with observed monitor data. The Speciated Modeled Attainment Test (SMAT) uses ambient monitor data and model outputs to estimate future concentrations.

Model results are used to determine relative reduction factors (RRFs), model-predicted percent changes in pollutant from base case to the scenario case. For pollutants like ozone, this is simple to calculate as there is only one component. For PM it is necessary to calculate individual RRF's for each of the $PM_{2.5}$ species (sulfates, nitrates, ammonium, organic carbon mass, elemental carbon, crustal, water, and blank mass). Total PM is reconstructed as the sum of the individual components.

SMATing consists of five basic procedures:

1) Derive quarterly mean concentrations of each PM component by multiplying FRM $PM_{2.5}$ by fractional composition of each species.
2) Calculate a model derived relative reduction factor for each species.
3) Multiply each RRF times each ambient $PM_{2.5}$ component (for each quarter) to get the future concentrations.
4) Sum the future quarterly average components
5) Average the four mean quarterly future $PM_{2.5}$ concentrations.

(Timin, 2005).

This preliminary analysis does not use SMATed data for the benefits analysis. Health impacts are predicted strictly from PM CMAQ model outputs. It should be noted that for the larger Energy Policy Act Study, SMATed data will be used in accordance with EPA procedure.

4.3 Benefit Analysis for the Removal of Commercial Aircraft Emissions

This section details the impacts on public health and the monetary valuation of these impacts that result from commercial aircraft emissions. The following sections review the methodologies most recently employed by EPA in conducting the Regulatory Impact Assessment for proposed locomotive engines and marine compression-engines rule (*Draft RIA Locomotive & Marine Rule*, 2007). The following section provides an overview of the salient features of the EPA recommended assessments and presents our preliminary results in a benefit analysis for the removal of aircraft emissions. Note again, that since the emissions inventories, local air quality analyses and PM speciation methods are not consistent with those of the larger Energy Policy Act Study, these results should only be considered as an illustration of the methods that will be used in the final Energy Policy Act Study. The numerical values of the health impacts should not be cited or quoted.

4.3.1 Health Endpoints

To measure commercial aircraft impact on public health this analysis relies on examining certain health effects, or endpoints. This analysis examines those health endpoints consistent with EPA.

To select health endpoints, the EPA receives input from the EPA Science Board Health Effects Subcommittee (SB-HES), a scientific review panel established to provide advice on the use of scientific literature in developing benefit analyses for air pollution regulations. In general, the EPA follows a weight of evidence approach based on the biological plausibility of effects, availability of concentration response functions from well conducted peer-reviewed epidemiological studies, cohesiveness of results across studies, and a focus on endpoints reflecting public health impacts rather than physiological response (*Draft RIA Locomotive & Marine Rule*, 2007). The health endpoints used for EPA benefit analyses are listed in Table 8.

Ozone-Related Health Endpoints	Mortality, Respiratory Hospital Admissions, School Loss Days, Worker Productivity, Minor Restricted Activity Days, Asthma-related ER visits
PM-Related Health Endpoints	Mortality, Respiratory Hospital Admissions, Cardiovascular Hospital Admissions, Chronic Bronchitis, Non-fatal Heart Attacks, Acute Bronchitis, Upper Respiratory Symptoms, Lower Respiratory Symptoms, Work Loss Days, Minor Restricted Activity Days, Asthma Exacerbation, Asthma-related ER visits

Table 8. Health Endpoint used for Benefit Analyses (Davidson, 2007)

The next section will describe how concentration response functions are used to estimate changes in these endpoints.

4.3.2 C-R Functions

Although the biological mechanisms responsible for the health effects of all pollutants have not been identified (especially for $PM_{2.5}$), epidemiological, toxicological, and experimental evidence supports an assumption of causality (*Draft RIA Locomotive & Marine Rule*, 2007) . The EPA examines epidemiological studies that relate the changes in pollutant concentration with observed health incidence and obtains the corresponding concentration response function.

Concentration response functions (C-R Functions) relate the change in the number of observed health events for a population with changes in ambient concentration of a particular air pollutant. Generally C-R Functions are assumed to have a log-linear form:

$$\Delta y = y_0 \cdot (e^{\beta \cdot \Delta P} - 1)$$

Where:

- y_0 is the baseline incidence
- B is the effect estimate provided by the study
- ΔP is the change in the concentration of the pollutant being examined

C-R functions are obtained from a variety of epidemiological studies, and the EPA uses a range of criteria when choosing studies that estimate C-R functions. These criteria include pier review, study size, and study location and are listed in Table 9.

Consideration	EPA Comments
Peer-Reviewed Research	EPA prefers peer reviewed research to research that has not undergone the peer-review process.
Study Type	Among studies that consider chronic exposure (e.g. over a year or longer), EPA prefers prospective cohort studies over ecological studies because they control for important individual-level confounding variables than cannot be controlled for in ecological studies.
Study Period	EPA prefers studies examining a relatively longer period of time (and therefore having more data) because they have greater statistical power to detect effects. More recent studies are also preferred, because of possible changes in pollution mixes, medical care, and lifestyle over time. However, when there are only a few studies available, EPA will include studies from all years.
Population Attributes	The most technically appropriate measure of benefits would be based on impact functions than cover the entire sensitive population but allow for heterogeneity across age or other relevant demographic factors. In the absence of effect estimates specific to age, sex, preexisting condition status, or other relevant factors, it may be appropriate to select effect estimates that cover the broadest population to match with the desired outcome of the analysis, which is total nation-level health impacts. When available, EPA prefers multi-city studies to single city studies because they provide a more "generalizable" representation of C-R functions
Study Size	EPA prefers studies examining a relatively large sample as they generally have more power to detect small magnitude effects. A large sample can be obtained in several ways, either through a large population or through repeated observations on a smaller population (e.g. through a symptom diary recorded for a panel of asthmatic children).
Study Location	U.S. studies are more desirable than non-U.S. studies because of potential differences in pollution characteristics, exposure patterns, medical care systems, population behavior, and lifestyle.
Pollutants Included in Model	When modeling the effects of ozone and PM (or other pollutant combinations) jointly, it is important to use properly specified impact functions that include both pollutants. Using single pollutant models in cases where both pollutants are expected to affect a health outcome can lead to double-counting when pollutants are correlated.

Measure of pollutant	For PM analyses, impact functions based on $PM_{2.5}$ are preferred to PM_{10} because of the focus on reducing $PM_{2.5}$ precursors, and because air quality modeling was conducted for this size fraction of PM. Where $PM_{2.5}$ functions are not available, PM_{10} functions are used as surrogates, recognizing that there will be potential downward (upward) biases if the fine fraction of PM_{10} is more (less) toxic than the coarse fraction.
Economically Valuable Health Effect	Some health effects, such as forced respiratory volume and other technical measurements of lung function, are difficult to value in monetary terms. These health effects are not quantified by EPA.
Nonoverlapping Endpoints	Although the benefit associated with each individual health endpoint may be analyzed separately, care must be exercised in selecting health endpoints to include in the overall benefit analysis because of the possibility of double-counting benefits.

Table 9. EPA C-R Function Selection Criteria (*EPA RIA PM NAAQS Ch.5*, 2006)

When more than one C-R function is available for a particular pollutant and a given health endpoint, the estimates are combined, or *pooled*, to derive a more robust estimate of the relationship. Fixed effects pooling weights the study's estimate based on the inverse variance. Random effects pooling weights studies based on in-study variance and between-study variance (for example, due to differences in population susceptibility). We assume random or fixed-effect pooling consistent with EPA.

The EPA cites many uncertainties inherent to virtually all PM C-R Functions (*Draft RIA Locomotive & Marine Rule*, 2007):

- *Causality*: Epidemiological studies do not prove causality. Instead, causality is assumed when examining correlations between PM and changes in incidences of premature mortality.
- *Other pollutants*: A variety of pollutants exist side by side. Specifically, PM and ozone concentrations are often correlated. It is possible that some health impacts can be assigned to the wrong pollutant.
- *Shape of the C-R Function*: The shape of the C-R function is uncertain. EPA assumes that C-R functions are non-threshold, log-linear functions, unless otherwise stated. There is an ongoing debate as to whether a threshold exists below which changes in ambient $PM_{2.5}$ have no effect on public health,
- *Regional Differences*: Significant variability exists including PM composition. Applying PM C-R functions outside of the region studied may misrepresent the true effects.
- *Relative Toxicity of PM Component Species*: Many studies are conducted with the assumption that all fine particles, regardless of their chemical composition are equally potent in causing premature mortality. While it is reasonable to guess that chemical components do affect potency, the EPA's interpretation of scientific evidence does not provide a basis from which to characterize beyond total PM mass.
- *Lag Time Between Change in Exposure and Health Impact*: There is a lag time between exposure and response, known as the cessation lag. This lag is unknown for the PM/mortality relationship.

- *Cumulative Effects*: The effects of cumulative exposure to PM (and other pollutants) are unknown at this time.

The EPA also cites various uncertainties associated with the use of C-R functions based on reported health effects estimates from epidemiological literature (*Draft RIA Locomotive & Marine Rule*, 2007):

- *Within-study variation*: Most studies provide a best estimate of the relationship between concentration and response with a statistical uncertainty. The size of uncertainty depends on factors such as the number of subjects studied and the size of the effect being estimated.
- *Across-Study Variation*: Different published studies of the same pollutant and health impact do not typically report identical finding. Differences in measurement techniques, study design, air quality monitoring techniques, averaging times, medical reporting are possible causes.
- *Application of C-R Relationships Nationwide*: Each impact function is applied uniformly across the nation regardless the possibility that some effects are region specific.
- *Extrapolation of Impact Functions across Populations*: Epidemiological studies often focus on a specific range of ages. If possible, C-R functions are applied to just the population examined for the study, but in some cases there is no biological reason that the health effect would not occur in the broader population. In these cases the EPA expands the age range to ensure that health effects are not underestimated.

Another major source of uncertainty stems from the use of four months of data. C-R functions are used to provide annual estimates based on concentration changes that account for only four summer months. While this captures the effects of some ozone seasons, estimates may be more problematic from $PM_{2.5}$. Still, it should be noted that the health impact analysis for the final study will be based on a full year's worth of air quality modeling.

The EPA aided by the Science Advisory Board Health Effects Subcommittee (SAB-HES) continues to set research priorities to alleviate some concerns over these uncertainties, but EPA continues to conduct health impact assessment fully aware of these concerns. The next section will describe how the EPA has worked to account for some of these uncertainties in estimating PM mortality with the use of expert elicitation.

4.3.3 Accounting for Uncertainty in $PM_{2.5}$ Mortality C-R Functions: Expert Elicitation

Epidemiological studies provide statistical errors to represent the uncertainty associated with a specific C-R function. This error is related more to factors such as population size and frequency of the measured outcomes. Still, there are other sources of uncertainty including model specifications and confounding factors as described above. While epidemiological studies provide direct concentration-response relationships, there are other sources such as toxicological studies and human clinical trials that contribute to the weight of evidence surrounding a particular health impact. One of the areas of greatest uncertainty surrounds the relationship between PM concentration and mortality. The EPA has explored this probabilistic causality using expert elicitation.

In 2002 the National Research Council (NRC) reviewed EPA's method for assessing health impacts and recommended that EPA incorporate the use of formal elicitation of experts to characterize the uncertainties in its estimates for rules affecting $PM_{2.5}$ (IEc, 2006). After conducting a pilot scale study with 5 experts in 2003 and 2004, and a second study of 12 experts in late 2004, EPA conducted a full-scale study with 12 health experts between January and April 2006.

Experts were chosen through a two-part peer nomination process that included eight experts in epidemiology, three in toxicology, and one in medicine (IEc, 2006). The peer review process was designed to designate a balanced set of views. The twelve experts chosen appear below in Table 10.

Name	**Affiliation**
Dockery, Doug W.	Harvard School of Public Health
Ito, Kazuhiko	New York University School of Medicine
Krewski, Daniel	University of Ottawa
Künzli, Nino	University of Southern California Keck School of Medicine (Currently at Institut Municipal d'Investigació Médica (IMIM) – Center for Research in Environmental Epidemiology, Barcelona, Spain)
Lippman, Morton	New York University School of Medicine
Mauderly, Joe	Lovelace Respiratory Research Institute
Ostro, Bart, D.	California Office of Environmental Health Hazard Assessment
Pope, C. Arden III	Brigham Young University
Schlesinger, Richard	Pace University
Schwartz, Joel	Harvard School of Public Health
Thurston, George D.	New York University School of Medicine
Utell, Mark	University of Rochester School of Medicine and Dentistry

Table 10. $PM_{2.5}$ Expert Elicitation Members (IEc, 2006)

Each elicitation interview was conducted for approximately 8 hours and began with qualitative question on the expert's beliefs concerning key evidence and critical sources of uncertainty. Experts were questioned on the following issues:

- Biological mechanisms that link $PM_{2.5}$ exposure to mortality,
- Key scientific evidence on the magnitude of the PM-mortality relationship,
- Sources of error or bias in epidemiological results,
- The probability of a causal relationship between $PM_{2.5}$ and mortality, and

- The shape of the C-R function.

The central quantitative question asked to each of the experts was to provide a probabilistic distribution for the average expected decrease in U.S. annual, adult all-cause mortality associated with a 1 $\mu g/m^3$ decrease in annual average $PM_{2.5}$ levels. To address this question, experts were asked to specify a functional form for the $PM_{2.5}$ mortality C-R function and then develop an uncertainty distribution for the slope of the function taking into account the evidence and judgments discussed during the qualitative questions (IEc, 2006).

Each expert was given the option to integrate their judgments into a causal relationship and/or threshold for the C-R function. They were asked to create a distribution or to provide a distribution "conditional on" one or both of these factors. Each expert was asked to characterize his distribution by assigning values to 5^{th}, 25^{th}, 50^{th}, 75^{th}, and 95^{th} percentiles (IEc, 2006).

After all interviews were conducted experts were convened for a post-elicitation workshop in which experts judgments were anonymously revealed. Experts were assigned letters A-K to represent their elicitation to preserve anonymity. Experts were given the opportunity to raise issues with any of the findings and were allowed to modify their responses privately if desired (IEc, 2006).

The resulting distributions represent a range of scientific opinion.

One of the twelve experts (Expert K) incorporated a threshold into his C-R function, and indicated that there was a 50% chance that the threshold existed. He cited cohort studies that show greater uncertainty in the C-R function at low levels as possible indicators for the existence of a threshold. The rest of the experts cited a lack of empirical evidence to support a threshold. However, three experts gave different effect estimate distributions above and below some point (IEc, 2006).

Based on the responses of the twelve experts, a set of 12 C-R functions for premature mortality can be constructed. Each expert's function has the form:
$\Delta y = y_0 \cdot (e^{\beta \cdot \Delta PM} - 1)$
Where:

- y_0 is the baseline incidence
- B is the effect estimate provided by the expert, and
- ΔPM is the change in $PM_{2.5}$

Some experts specified piecewise log-linear functions, and multiple equations were developed to account for different ambient concentration levels. A third form was constructed to account for Expert K who provided both a piece-wise log-linear model as well as a probabilistic threshold. Expert K did not provide a distribution for the probability of the threshold, but provided a probability for a threshold between 0 and 5 $\mu g/m^3$ (40% chance) and another for a threshold between 5 to 10 μ/m^3 (10% chance). A Monte Carlo analysis with an assigned weight (0.4 for the first threshold, 0.1 for the second threshold, and 0.5 for no threshold) for each of Expert K's function resulted in 3 conditional functions (IEc, 2006).

Six of the experts chose a normal distribution to represent the distribution of the effect size in terms of the percent change in mortality associated with a 1 μg change in annual mean $PM_{2.5}$. One specified a triangular distribution, and one chose a Weibull distribution. Four experts did not provide a distribution, but assigned values to each percentile. For these distributions, a smooth, continuous distribution was assigned (IEc, 2006) .

In one case, Expert E provided a normal distribution that implied a negative tail at the 2.5^{th} percentile, but expressed a minimum value of zero. In this case the distribution was truncated. The mean was shifted up relative to a full normal (IEc, 2006) .

In some cases, experts included in their distribution the likelihood that $PM_{2.5}$ and mortality was not causal. In these cases, the distributions are unconditional and include zero with some probability. However, in most cases, the expert chose to specify a conditional distribution, such that the estimate is conditional on there being a causal relationship. In these cases the final distribution is the expected value of the unconditional distribution. This was done by estimating each expert's conditional distribution and then, using Monte Carlo sampling, construction an unconditional distribution using the experts reported causal relationship probability (IEc, 2006).

Following the lead of EPA, the following analysis explores the use of expert elicitation to characterize the C-R functions used for $PM_{2.5}$. The results of the expert elicitation are given along with the results from other studies when estimating the $PM_{2.5}$ mortality impacts.

4.3.4 Studies used for Health Impact Analysis

The EPA relies on published literature to quantify the relationship between pollutants and adverse human effects. The following studies are used by EPA to estimate C-R functions for the ozone and PM health impacts analysis.

Studies Used by EPA to Calculate Ozone Benefits

Premature Mortality

Premature mortality estimates are obtained from three meta-analysis studies sponsored by EPA (Bell, Dominici, & Samet, 2005; Ito, De Leon, & Lippmann, 2005; Levy, Chemerynski, & Sarnat, 2005) as well as a multi-city study (Bell, Samet, & Dominici, 2004). For this analysis we use the estimate provided by Levy et al., but we will follow the direction of EPA in selecting appropriate estimates for the Energy Policy Act Study.

Respiratory Hospital Admissions

Respiratory hospital admissions are estimated by looking at two groups, adults over 65 and children under 2. For adults over 65, results are first pooled based on respiratory causes.

Pneumonia: Moolgavkar et al. and Schwarz (1994a) examine hospital admissions in Minneapolis and Schwartz (1994b) examine admissions in Detroit (Moolgavkar, Luebeck, & Anderson, 1997; Schwartz, 1994a, 1994b). Impact functions for Minneapolis are pooled first to prevent too much weight being assigned to responses in Minneapolis. This result is then pooled with the Detroit impact function from Schwartz (1994b).

Chronic Obstructive Pulmonary Disease (CPOD): A pooled estimate from Moolgavkar et al. and Schwartz is used to estimate health incidences of CPOD (Moolgavkar et al., 1997; Schwartz, 1994a).

To estimate total hospital admissions for adults over 65, COPD admissions were added to pneumonia admissions and the results were pooled with Schwartz (Schwartz, 1995), an all-cause respiratory admission estimate.

For children under 2, only one estimate for respiratory hospital admissions is provided (Burnett et al., 2001).

School Loss Days

EPA uses two studies to estimate changes in school absences for children (ages 5-17). Gilliland et al. estimated the incidence of new periods of absences for 9 and 10 year olds, while Chen studied absence on a given day for 6-11 year olds (Chen, Jennison, Yang, & Omaye, 2000; Gilliland et al., 2001). Gilliand's estimate is converted by multiplying the absence period by the average duration of an absence. The average duration of an absence is estimated by dividing the average daily school absence rate from Chen and Ransom and Pope (Ransom & Pope, 1992) by the episodic absence rate from Gilliland. This provides estimates from Chen et al. and Gilliland et al. that can be pooled. The age range for these studies was extended to encompass a broader range, ages 5 to 17.

Worker Productivity

Cocker and Horst analyzed the relationship between ozone levels and worker productivity among citrus pickers in Southern California (Cocker & Horst, 1981). This impact function is applied to all outdoor workers ages 18-65.

Minor Restricted Activity Days

Minor restricted activity days (MRADs) result when individuals reduce most usual daily activities and replace them with less stringent activities or rest, but do not miss work of school (*EPA RIA PM NAAQS Ch.5*, 2006). This effect is estimated based on the work of Ostro & Rothschild (Ostro & Rothschild, 1989).

Asthma-Related Emergency Room Visits

Ozone induced asthma-related emergency room visits for the entire population is handled by pooling estimates from Cody et al., Weisel et al., and Steib et al. (Cody, Weisel, Birnbaum, & Lioy, 1992; Stieb, Burnett, Beveridge, & Brook, 1996; Weisel, Cody, & Lioy, 1995)

Table 11 lists the endpoint and studies used for the ozone benefit analysis.

Endpoint	Pooling	Study	Study Population
Premature Mortality	None	Bell et. al. (2004)	All ages: 0-99
		Bell et. al. (2005)	
		Ito et. al (2005)	
		Levy et. al. (2005)	
Hospital Admissions: All Respiratory	Pooled	Moolgavkar (1997) (Pneumonia)	65-99
		Moolgavkar (1997) (COPD)	65-99
		Schwartz (1994a) (Pneumonia)	65-99
		Schwartz (1994b) (Pneumonia)	65-99
		Schwartz (1994) (COPD)	65-99
		Schwartz (1995)	65-99
	None	Burnett et. al. (2001)	Infants: 0-1
School Loss Days	Pooled	Chen et. al. (2000)	Children: 5-17
		Gilliland et. al. (2001)	
Worker Productivity	None	Cocker and Horst (1981)	Outdoor workers: 18-64
Acute Respiratory Symptoms: Minor Restricted Activity Days	None	Ostro and Rothschild (1989)	18-65
Asthma-Related Emergency Room Visits	Pooled	Weisel et. al. (1995)	Asthmatics, All ages: 0-99
		Cody et. al. (1992)	
		Stieb et. al. (1996)	

Table 11. Endpoints and Studies for Ozone Benefit Analysis (Davidson, 2007)

Studies Used by EPA to Calculate $PM_{2.5}$ Benefits

Adult Premature Mortality

The most extensive analyses have been based on data from two prospective cohort studies, the Harvard "Six Cities Study" (Dockery et al., 1993; Laden, Schwartz, Speizer, & Dockery, 2006) and the "American Cancer Society (ACS) Study" (Pope et al., 2004; Pope et al., 1995; Pope et al., 2002). Both studies found consistent relationships between premature mortality and exposure to fine particles. The Expert Elicitation Study as described above is used to provide 12 additional estimates for PM-related mortality.

EPA recommends that PM-related premature mortality benefits be estimated based on an assumed cutoff point in the concentration-response curve. Reflecting comments from the Clean Air Scientific Advisory Committee (CASAC), EPA assumes a 10 μg/m3 threshold below which it is assumed the PM levels have no effect on mortality (*Draft RIA Locomotive & Marine Rule*, 2007).

Infant Mortality

The EPA uses a study by Woodruff et al. (Woodruff, Grillo, & Schoendorf, 1997) because the SAB-HES notes several strengths in this study as compared to others, including use of a larger cohort drawn from a number of metropolitan areas and effort to control for a variety of individual risks factors in infants (e.g. maternal education level, maternal ethnicity, parental marital status, and maternal smoking status). Based on these findings, the SAB-HES recommended that EPA incorporate infant mortality into benefit estimates (*EPA RIA PM NAAQS Ch.5*, 2006).

Chronic Bronchitis

Chronic bronchitis (CB) is characterized by mucus in the lungs and a persistent wet cough for at least 3 months. Schwartz (Schwartz, 1993) and Abbey et al. (Abbey, Hwang, Burchette, Vancuren, & Mills, 1995) both provide evidence that long term PM exposure gives rise to the development CB, but only Abbey focuses on new cases of CB. Thus, EPA recommends using only the impact function of Abbey et al. (*EPA RIA PM NAAQS Ch.5*, 2006)

Nonfatal Myocardial Infarctions (Hearth Attacks)

While a recent study by Zanobetti and Schwartz found a correlation between PM concentration and nonfatal heart attacks, this study uses PM_{10} as an indicator and encompasses a limited age range (Zanobetti & Schwartz, 2005). There are also other studies that relate to all cardiovascular hospital admissions, but the long-lasting impacts of heart attacks require a separate estimate. The study by Peters and Dockery (Peters & Dockery, 2001) is used because it represents the only study that uses $PM_{2.5}$ as the PM indicator.

Hospital Admissions: All Respiratory

To estimate total avoided costs for respiratory hospital admissions, EPA uses impact functions for several respiratory causes: chronic obstructive pulmonary disease (COPD), pneumonia, and asthma. Additional studies show correlations between PM_{10} and these respiratory causes; however, EPA uses only those studies that focus on $PM_{2.5}$. Both Moolgavkar (Moolgavkar, 2000) and Ito (Ito, 2003) provide COPD estimates for population over 65, and the estimates are pooled. In addition, only Moolgavkar provides an estimate for the effects on the population age 20-64. Ito provides an estimate for pneumonia admissions for the population over 65 as well. Shepperd (Sheppard, 2003) provides effect estimates for asthma admissions for the population ages 20-64. The total number of PM-related respiratory admissions is obtained by summing COPD, pneumonia, and asthma admissions estimates.

Hospital Admissions

To avoid double counting, the baseline cardiovascular hospital admissions were adjusted to exclude myocardial infarctions. Cardiovascular hospital admissions are the sum of pooled estimate from Moolgavkar (Moolgavkar, 2003) and Ito (Ito, 2003) for population over 65. Cardiovascular hospital admissions for 20-64 year olds were estimated by Moolgavkar (Moolgavkar, 2000).

Asthma-Related Emergency Room Visits

The EPA estimates ER visits for asthmatics under 18 with a study by Norris et al. (Norris et al., 1999). This study was selected because of its focus on $PM_{2.5}$ as opposed to PM_{10}. Because children tend to have higher hospitalization rates for asthma than the total population under 65, a large part of the effects are captured with this estimate. However, there may still be significant impacts in the population under 65 that have not been captured.

Upper & Lower Respiratory Symptoms

Asthmatics are more susceptible to a variety of respiratory symptoms. Studies on the effects of upper respiratory symptoms, such as runny or stuffy nose, wet cough, burning, aching, or red eyes focus solely on asthmatics. Effects on asthmatics ages 9-11 are covered with an estimate developed by Pope et al. (Pope, Dockery, Spengler, & Raizenne, 1991). Schwartz and Neas (Schwartz & Neas, 2000) examine incidences of lower respiratory symptoms (e.g. wheezing or deep cough) in schoolchildren, ages 7 to 14.

Minor Restricted Activity Days and Work Loss Days

Minor restricted activity days (MRADs) result when individuals reduce most usual daily activities and replace them with less stringent activities or rest, but do not miss work of school (*EPA RIA PM NAAQS Ch.5*, 2006). This effect is estimated based on the work of Ostro & Rosthschild (Ostro & Rothschild, 1989). Work loss days are estimated by Ostro (Ostro, 1987).

Asthma Exacerbation

The EPA pools the estimates of Ostro et al. (Ostro, Lipsett, Mann, Braxton-Owens, & White, 2001) and Vedal et al. (Vedal, Petkau, White, & Blair, 1998) to estimate asthma exacerbations in children. Ostro et al. found correlations between $PM_{2.5}$ and shortness of breath and wheezing. Although Ostro et al. found association with $PM_{2.5}$ and cough that were not statistically significant, they were very close to statistically significant and therefore included. Vedal et al. found a significant negative correlation between $PM_{2.5}$ exposure and peak expiratory flow (PEF), a measure of how fast air can be exhaled from the lungs, in addition to other respiratory symptoms (cough, phlegm, wheeze, chest tightness). PEF is difficult to clearly-define as a health endpoint; therefore only the cough-related endpoints were included. All of the Ostro et al. endpoints were pooled, and then this final estimate was pooled with the Vedal et al. estimate. The applicable population was extended to include 6 to 18 year olds. Asthma exacerbations in adults are assumed to be captured in other endpoints such as work loss days and minor restricted activity days.

Table 12 lists the endpoint and studies used for the $PM_{2.5}$ benefit analysis.

Endpoint	Pooling	Study	Study Population
Premature Mortality	None	Pope et al. (2002)	29-99
	None	Laden et al. (2006)	25-99
	None	Expert Elicitation	24-99
	None	Woodruff et al. (1997)	Infants: 0-1
Chronic Bronchitis	None	Abbey et al. (1995)	27-99
Nonfatal Heart Attacks	None	Peters et al. (2001)	Adults
Hospital Admissions: Respiratory	Pooled	Moolgavkar (2000): COPD	65-99
		Ito (2003): COPD	
	None	Moolgavkar (2000): COPD	20-64
	None	Ito (2003): Pneumonia	65-99
	None	Sheppard (2003): Asthma	65-99
Hospital Admissions: Cardiovascular	Pooled	Moolgavkar (2003): All cardiovascular	65-99
		Ito (2003): Ischemic heart disease, dysrhythmia, heart failure	
	None	Moolgavkar (2000)	20-64
Asthma-Related ER Visits	None	Norris et al. (1999)	Asthmatics: 0-18
Acute Bronchitis	None	Dockery et al. (1996)	8-12
Upper Respiratory Symptoms	None	Pope et al. (1991)	Asthmatics: 9-11
Lower Respiratory Symptoms	None	Schwartz and Neas (2000)	7-14
Asthma Exacerbations	Pooled	Ostro et al. (2001): Cough, Wheeze, Shortness of Breath	6-18
		Vedal et al. (1998): Cough	
Work Loss Days	None	Ostro et al. (1987)	18-65
MRADs	None	Ostro and Rothschild (1989)	18-65

Table 12. Endpoints and studies for $PM_{2.5}$ Benefit Analysis (Davidson, 2007)

4.3.5 Baseline Health Effect Incidence Rates

Epidemiological studies generally provide relative estimates for changes in adverse effects (e.g. 3% decrease in asthma exacerbations), rather than absolute changes in incidences. To convert this relative change into a total number of cases, an estimate of a baseline incidence rate is necessary.

EPA obtains baseline incidence rates for the initial number of cases of a health effect per year from a number of sources:

- For premature mortality, Age- and County-specific mortality rates are estimated using Center for Disease Control (CDC) data. The U.S. Centers for Disease Control (CDC) maintains an online database of health statistics, CDC Wonder, to provide these estimates. These estimates are derived from the U.S. Census Bureau postcensal population estimates. For all other endpoints a single national incidence rate is used. To provide a more stable estimate, EPA averages mortality rates across 3 years (1996-1998). When estimating rates for age groups that differ from CDC groupings, rates are assumed to be uniform across all ages in the reported age group.
- For some endpoints, the only available incidence data is contained in the studies being examined. In this case, the incidence rates of the study population are assumed to adequately represent the national population.
- The National Hospital Ambulatory Medical Care Survey (NHAMCS) and National Hospital Discharge Survey (NHDS), a probability survey conducted annually since 1965 to characterize inpatients discharged from non-Federal short-stay hospitals in the U.S., are used to estimate incidences of several endpoints. The NHDS collects data from a sample of approximately 270,000 inpatient records acquired from a national sample of about 500 hospitals (*NHDS Data*, 2007).
- The American Lung Association estimates incidences in chronic bronchitis in children.

Table 13 contains baseline incidence rates for the general population.

Endpoint	Parameter	Incidence Value	Source
Mortality	Daily or Annual Mortality Rate	Age-, Cause-, and County-Specific Rate	CDC Wonder
Hospitalizations	Daily Hospitalization Rate	Age-, Region-, and Cause-Specific Visit Rate	National Hospital Discharge Survey Data (*NHDS Data*, 2007)
Asthma ER Visits	Daily Asthma ER Visit Rate	Age- and Region-Specific	National Hospital Discharge Survey (NHDS) & National Hospital Ambulatory Medical Care Survey

			(NHAMCS) (*NHDS Data*, 2007)
Chronic Bronchitis	Annual Prevalence Rate per person by age	18-44: 0.0367 45-64: 0.0505 65+: 0.0587	1999 National Health Interview Survey (NHIS) (*American Lung Association-b*, 2002)
	Annual Incidence Rate per person	0.00378	(Abbey et al., 1993)
Nonfatal Myocardial Infarction	Daily rates per person 18+ by region	Northeast: 0.0000159 Midwest: 0.0000135 South: 0.0000111 West: 0.0000100	1999 NHDS public use data files, adjusted for survival rate after 28 (Rosamond et al., 1999)
Asthma Exacerbations	Incidence and Prevalence among asthmatic African-American children	Daily Wheeze: 0.076 (0.173) Daily Cough: 0.067 (0.145) Daily shortness of breath: 0.037 (0.074)	(Ostro et al., 2001)
	Prevalence among asthmatic children	Daily Wheeze: 0.038 Daily Cough: 0.086 Daily shortness of breath: 0.045	(Vedal et al., 1998)
Acute Bronchitis	Annual Rate[5], Children	0.043	(*American Lung Association-a*, 2002)
Lower Respiratory Symptoms	Daily Rate, Children	0.0012	(Schwartz et al., 1994)
Upper Respiratory Symptoms	Daily Rate, Asthmatic Children	0.3419	(Pope et al., 1991)
Work Loss Days	Daily Rate, by Age	18-24: 0.00540 25-44: 0.00678 45-64: 0.00492	(Adams, Hendershot, & Marano, 1999)
Minor Restricted Activity Days	Daily Rate per person	0.02137	(Ostro & Rothschild, 1989)

Table 13. Baseline Incidence Rates for Use in Impact Functions, General Population (*Draft RIA Locomotive & Marine Rule*, 2007).

For endpoints that affect asthmatic populations, asthma prevalence rates must be obtained as well. The EPA obtains this data from the American Lung Association as well as the Center for Disease Control (CDC) Health Interview Survey (HIS).

[5] Defined as two or more of the following: cough, chest pain, phlegm, or wheeze

Table 14 contains asthma prevalence rates.

Population Group	Value	Source
All Ages	0.0386	(*American Lung Association-b*, 2002)
<18	0.0527	(*American Lung Association-b*, 2002)
5-17	0.0567	(*American Lung Association-b*, 2002)
18-44	0.0371	(*American Lung Association-b*, 2002)
45-64	0.0333	(*American Lung Association-b*, 2002)
65+	0.0221	(*American Lung Association-b*, 2002)
Male, 27+	0.021	HIS Public Use Data Files (*National Health Interview Survey (NHIS)*, 2007)
African American, 5 to 17	0.0726	(*American Lung Association-b*, 2002)
African American <18	0.0735	(*American Lung Association-b*, 2002)

Table 14. Asthma Prevalence Rates (*Draft RIA Locomotive & Marine Rule*, 2007)

4.3.6 Valuation of Health Endpoints

Changes in concentration of pollutants reduce the risk of future adverse effects ex ante (before the event has occurred). To value such impacts an appropriate economic measure is *willingness to pay* (WTP). An individual's *willingness to accept* (WTA) compensation for not receiving the improvement is also a valid measure; however, EPA considers WTP estimates more readily available and as conservative measures of the benefits. For some instances, such as fatal risk reductions, the EPA uses WTA estimates due to the difficulty in obtaining WTP estimates. (*Draft RIA Locomotive & Marine Rule*, 2007).

Epidemiological studies generally provide an estimate of the relative risk created by elevated levels of a certain pollutant. The EPA uses this data by converting probabilities to units of avoided statistical incidences. This is done by dividing WTP for a risk reduction by the related observed change in risk. This approach takes into account the size of the population.

For some endpoints such as hospital admissions, WTP estimates are generally not available. In this case, cost of illness (COI) estimates are used instead.

Following the recommendation if the Environmental Economics Advisory Committee (EEAC) of the SAB, the EPA uses a value of statistical life (VSL) approach. Using the VSL approach, EPA is able to value a small change in mortality risk experienced by a large number of people. Still, many factors affect the degree to which mortality risk affects an individual. For example, some age groups are more susceptible to air pollution, and an ideal benefit estimate would reflect human characteristics. An ideal analysis would also include an individual's WTP to increase the survival rate of others in addition to WTP for her own survival.

The EPA recognizes other uncertainties related to premature mortality valuation:

- *Across-Study Variation*: The majority of studies relied on by the EPA involve the valuation of risk to a middle-aged working population. WTP is affected by characteristics that vary from the population studied to those affected by changes in air quality.
- *Level of Risk Reduction*: Transferring wage-risk study results to the context of air pollution implies that WTP for mortality risks are linearly tied to risk reduction. Under the assumption of linearity, the value of a statistical life (VSL) does not depend on the particular amount of risk reduction to be valued. This assumption has been shown to be reasonable as long as the change in risk is within the range of risk of the underlying studies (*EPA RIA PM NAAQS Ch.5*, 2006).
- *Voluntariness of Risks Evaluated*: The EPA acknowledges that job-related mortality risks are incurred voluntarily while air-pollution related risks are assumed completely involuntarily. The EPA suggests that WTP on wage-risk studies may undervalue WTP to reduce involuntary air pollution-related mortality risks.
- *Sudden versus Protracted Death*: Workplace mortality estimates stem from risks that often involve sudden, catastrophic events whereas air pollution risks often deal with longer periods of disease and suffering. There is evidence that suggests that WTP to avoid risk of a protracted death involving prolonged suffering and loss of dignity is greater than WTP to avoid sudden death.
- *Self-selection and Skill in Avoiding Risk*: The EPA acknowledges that hedonic studies that assume that workers get higher wages for jobs that are most dangerous, may overstate the average value of risk reduction. Risk-wage trade-offs reveled in hedonic studies reflect the preferences of the marginal worker (e.g. the worker who demands the highest compensation for risk reduction). Shogren and Stamland have shown an upward bias. (Shogren & Stamland, 2002)
- *Baseline Risk and Age*: Recent research finds that because individuals reevaluate their baseline risk of death as they age, the marginal value of risk reduction does not decline with age as predicted by some lifetime consumption models. This suggests only small reductions on the value of mortality with age.

The EPA obtains valuation estimates from a number of studies. The range of valuations is given as a distribution obtained from one or in some cases multiple sources. Table15 provides the central estimate used for each endpoint.

Health Endpoint	Derivation of Estimate	Central Estimate of Central Estimate for Value Per Statistical Incidence (1990 Income Level)
Premature Mortality	Point estimate is the mean of a normal distribution with a 95% confidence interval between $1 and $10 million. EPA uses two meta-analyses of wage-risk value of statistical life (VSL) literature. $1 million was taken from the lower end of the interquartile range given by Mrozek and $10 million is obtained from the upper end of the interquartile range given by Viscuzi and Aldy. (Mrozek & Taylor, 2002; Viscusi & Aldy, 2003)	$5,500,000
Chronic Bronchitis (CB)	Point estimate is the mean of a generated distribution of WTP to avoid a case of pollution related CB. WTP estimates are adjusted based on the work of Viscuzi et. al (Viscusi, Magat, & Huber, 1991). The WTP studies involved only severe cases of CB, so the estimate was adjusted to account for differences in severity and taking into account the elasticity of WTP with respect to severity of CB as suggested by Krupnik and Cropper (Krupnick & Cropper, 1992). The distribution of WTP estimates is obtained from uncertainties from three sources: the WTP uncertainty described by Viscuzi et. al., estimates of the severity level of an average case of CB, and the elasticity of WTP with respect to the severity of the illness.	$340,000
Nonfatal Myocardial Infarction	The EPA uses age related cost-of-illness (lost earnings and direct medical cost) values to reflect lost earnings and direct medical costs over a 5-year period following a non-fatal myocardial infarction. Lost earnings are taken from Cropper and Krupnik, and direct medical costs are based on the average of the estimates provided by Russell et al. and Wittels et al. (Cropper & Krupnick, 1990; Russell, Huses, Drowns, Hamel, & Hartz, 1998; Wittels, Hay, & Gotto, 1990). Lost earnings are not estimates for the population under 25 or over 65. The values were produced assuming a 3% discount rate for cost incurred over multiple years.	0-24: $66,902 25-44:$74,676 45-54:$78,834 55-65: $104,649 66+: $66,902
Hospital Admissions		
Chronic Obstructive Pulmonary Disease (CPOD)	The EPA uses cost-of illness estimates of lost earnings plus direct medical costs reported by the Agency for Healthcare Research and Quality. The Agency estimates average hospital care costs, average length of hospital stay, and weighted share of total COPD.	$12,378

	International Statistical Classification of Diseases and Related Health Problems (ICD) codes are used (ICD-9 code-level information). (*HCUPnet Healthcare Cost and Utilization Project*, 2000)	
Pneumonia	The EPA uses cost-of-illness estimates of lost earnings plus direct medical costs reported by the Agency for Healthcare Research and Quality. The Agency estimates average hospital care costs, average length of hospital stay, and weighted share of total pneumonia. (*HCUPnet Healthcare Cost and Utilization Project*, 2000)	$14,693
Asthma	The EPA uses cost-of-illness estimates of lost earnings plus direct medical costs reported by the Agency for Healthcare Research and Quality. The Agency estimates average hospital care costs, average length of hospital stay, and weighted share of total asthma. (*HCUPnet Healthcare Cost and Utilization Project*, 2000)	$6,634
All Cardiovascular	The EPA uses cost-of-illness estimates of lost earnings and plus direct medical costs reported by the Agency for Healthcare research and Quality. The Agency estimates of average hospital care costs, average length of hospital stay, and weighted share of total cardiovascular category illnesses. (*HCUPnet Healthcare Cost and Utilization Project*, 2000)	$18,387
Asthma ER Visits	The EPA uses an average of two cost-of-illness estimates from Smith et al. and Stanford et al. (Smith et al., 1997; Stanford, McLaughlin, & Okamoto, 1999)	$286
Respiratory ailments: No hospitalization Required		
Upper Respiratory Symptoms	The EPA combines the three symptoms for which WTP estimates are available that closely match those observed by Pope et al. Seven "symptom clusters" result, each describing a "type" of upper respiratory symptom. EPA derives a dollar value for each symptom cluster, using a mid-range estimate from Industrial Economics, Incorporated (IEc) assuming additivity of WTP. The resulting value is given by the average of the seven types of upper respiratory symptom. (IEc, 1994)	$25
Lower Respiratory Symptoms	The EPA uses a combination of the four symptoms for which WTP estimates are available that closely resemble those observed by Schwartz et al. Eleven "symptom clusters" ("types") result. A dollar value was assigned to each type of symptom using IEc estimates. The average of the WTP estimates for the 11 types is used. (IEc, 1994)	$16
Asthma Exacerbations	The EPA uses a $42 estimates based on the mean WTP estimate for the four severity definitions of a "bad asthma day" described by Chestnut and Rowe. The	$42

	Chestnut and Rowe study surveyed asthmatics to estimate WTP for avoidance of a "bad day" as defined by the study participants. The EPA assumes that an asthma attack is equivalent to a day in which asthma is moderate or worse as reported in Chestnut and Rowe. (Rowe & Chestnut, 1986)	
Acute Bronchitis	The EPA assumes a 6-day episode with daily value average equal to the average of low and high values for related respiratory symptoms recommended by Neumann et al. (Neumann, Dickie, & Unsworth, 1994) The low daily estimate of $10 is the sum of the mid-range values recommended by IEc ((IEc), 1994) for two symptoms believed to be associated with acute bronchitis: coughing and chest tightness. The high value was taken to be twice the value of a minor respiratory restricted activity day: $110 (*EPA RIA PM NAAQS Ch.5*, 2006).	$360
Restricted Activity & Work/School Loss days		
Work Loss Days (WLD's)	The EPA uses county-specific median annual wages divided by 50 (assuming two weeks of vacation) and then by 5-to get to median daily wage. The results are based on 2000 census data compiled by Geolytics, Inc. (Davidson, 2007)	
School Absence Days	This estimate is based on expected lost wages from parents staying home with child. Daily lost wage is based on median weekly wage among women age 25 and older. This median ($552) divided by 5 gives $103. The expected loss wage is estimated as the probability that the mother is in the workforces times the daily wage she would lose: 72.85% of $103, or $75. (Davidson, 2007)	$75
Worker Productivity	This estimate is based on the Bureau of Labor Statistics median daily earnings of workers in farming, forestry, and fishing. (Davidson, 2007)	$0.95 per worker per 10% change in ozone per day
Minor Restricted Activity Days (MRADs)	The EPA uses a median WTP estimate to avoid one MRAD from Tolley et al. (Tolley & et.al., 1986)	$51

Table 15. Unit values used for Valuation of Health Endpoints (*Draft RIA Locomotive & Marine Rule*, 2007)

4.3.7 Health Impact Analysis Results

The following section describes the health impact analysis that was done using the above concentration response, pooling, incidence rates, and valuation specifications. The analysis was done using the Environmental Benefits Mapping and Analysis Program (BenMAP), a computer program developed by EPA. BenMAP integrates numerous modeling elements necessary to calculate benefits including health impact functions, valuation functions, and analysis and pooling methods. The results for the ozone and PM benefit analysis appear below.

Mean incidence rates and mean estimated monetary values are given with the 5th and 95th percentiles in Table 16 and Table 17. Expert elicitation results for $PM_{2.5}$ mortality are given in Table 18.

Health Effect	Mean Incident Reduction (5th –95th Percentile)	Estimated Monetary Value (Million $) (5th – 95th Percentile)
Premature Mortality (Levy et al.)	-48 (-36 to -61)	-270 (-480 to -85)
Hospital Admissions: Respiratory Infants (Ages 0-1)	-61 (-32 to –90)	-0.47 (-0.70 to -0.25)
Hospital Admissions: Respiratory	-130 (-250 to -18)	-2.4 (-4.7 to -0.34)
School Loss Days	-26,000 (-43,000 to -10,000)	-2.0 (-3.2 to -.76)
Worker Productivity	-940,000 (-940,000 to -940,000)	-0.94 (-.94 to -.94)
Acute Respiratory Symptoms: Minor Restricted Activity Days	-82,000 (-42,000 to -120,000)	-4.1 (-8.7 to -1.3)
Asthma-Related Emergency Room Visits	-22 (-37 to -8)	-.0063 (-.014 to -.0022)

Table 16. Reduction in Ozone-Related Adverse Health Incidences and the Corresponding Valuation associated with the Removal of Aircraft Emissions

Health Effect	Mean Incident Reduction (5^{th}-95^{th} Percentile)	Estimated Monetary Value (Million $) ($5^{th}$ – 95^{th} Percentile)
Premature Mortality: Total Exposures (Pope et al. –10 μg threshold))	650 (250 – 1000)	3,600 (800 to – 7,100)
Infant Premature Mortality	1.7 (.82 – 2.5)	9.2 (2.3 to 18)
Chronic Bronchitis	400 (70 – 720)	130 (10 – 430)
Hospital Admissions: Respiratory	50 (30 – 70)	.87 (.46 – 1.3)
Nonfatal Heart Attacks	1200 (600 – 1700)	96 (25 – 190) (3% Discount Rate)
Hospital Admissions: Cardiovascular	Ages: 20-64 110 (70 – 160)	2.5 (1.5 – 3.6)
	Ages 65+ 190 (120 – 250)	4.0 (2.5 – 5.4)
Asthma-Related ER Visits	630 (370 – 890)	.18 (.10 – .27)
Acute Bronchitis	1500 (-50 to 3,000)	.52 (-.02 – 1.3)[6]
Upper Respiratory Symptoms	9,700 (3,000 – 16,00)	.25 (.07 – .52)
Lower Respiratory Symptoms	13,000 (6,300 – 20,000)	.21 (.08 – .37)
Asthma Exacerbations	12,000 (1,000 – 34,000)	.51 (.05 – 1.4)
Work Loss Days	82,000 (72,000 – 93,000)	10 (9.1 – 12)
Acute Respiratory Symptoms: MRADs	480,000 (410,000 – 550,000)	24 (14 – 35)

Table 17. Reduction in PM-Related Adverse Health Incidences and the Corresponding Valuation associated with the Removal of Aircraft Emissions

[6]Acute bronchitis estimates are not statistically significant, but very close. This results in a negative tail.

Source of $PM_{2.5}$ Mortality Estimate	Mean Estimate (5^{th} -95^{th} Percentile)
Pope et. al (2002)	650 (250 – 1,000)
Expert A	1,800 (350 – 3,360)
Expert B	1,100 (150 – 2,200)
Expert C	1,400 (480 – 2,300)
Expert D	1,000 (210 – 1,610)
Expert E	2,300 (1,200 – 3,500)
Expert F	950 (630 – 1,300)
Expert G	820 (0 – 1,500)
Expert H	1,000 (0 – 2,300)
Expert I	1,400 (280 – 2,400)
Expert J	1,100 (180 – 2,300)
Expert K	170 (0 – 750)
Expert L	750 (10 – 1,370)

Table 18. Results of Expert Elicitation Functions: Reduction in Premature Mortality associated with the Removal of Aircraft Emissions

5.0 Conclusion

Commercial aircraft contribution to county inventories in nonattainment areas is a metric shaped by many factors including the number of aircraft operations and county economic development. These estimates represent a broad range of scenarios accounting for a variety of county industrial and service economies and total aircraft operations ranging from less than 4,000 to over 505,000 per county per year.

Aircraft contribution to county budgets is an indicator that must be used with care. Transport processes transcend county divisions and several airports straddle county borders. The Clean Air Interstate Rule (CAIR) recognizes the impact that upwind sources may have on downwind nonattainment areas, and aircraft emissions from clearly defined commercial service airports are no exception. Moreover, airports outside of these counties may also have an influence on the nonattainment of these counties.

It is also important to note that pollutants emitted during landing and take off (LTO emissions) may not account for all local air quality impacts sourced to aircraft. Notably, recent studies have suggested that NO_X emissions at cruise altitude may have significant effects on ambient concentrations of secondary pollutants such as ozone (Tarrason, Jonson, Berntsen, & Rypdal, 2004).

Still, county emissions resulting from aircraft taxi, takeoff and arrival are a first order measure of aviations' influence on local air quality in nonattainment areas, especially when framed in the context of operational efficiency. This measure is a rough indicator of the need for terminal area initiatives aimed at curbing the emission of harmful pollutants and decreasing fuel burn.

The high relative contribution of aircraft NO_X and SO_X to the county budgets for many eastern states may increase. Aircraft may play an even more significant role in secondary PM formation in the wake of CAIR. The average SO_X contribution by aircraft to county budgets is 1.39%, and there are 3 airports that contribute between 10 and 40% to total budgets of SO_X. The average NO_X contribution is 1.73%, and there are 5 airports that contribute between 10 and 30% to total budgets of NO_X. Policy-makers must not neglect the role that secondary particulates may play with efforts to characterize primary PM from aircraft engines. Figure 15 shows the percent contribution by aircraft to county budgets of $PM_{2.5}$ and precursor emissions, NO_X and SO_X.

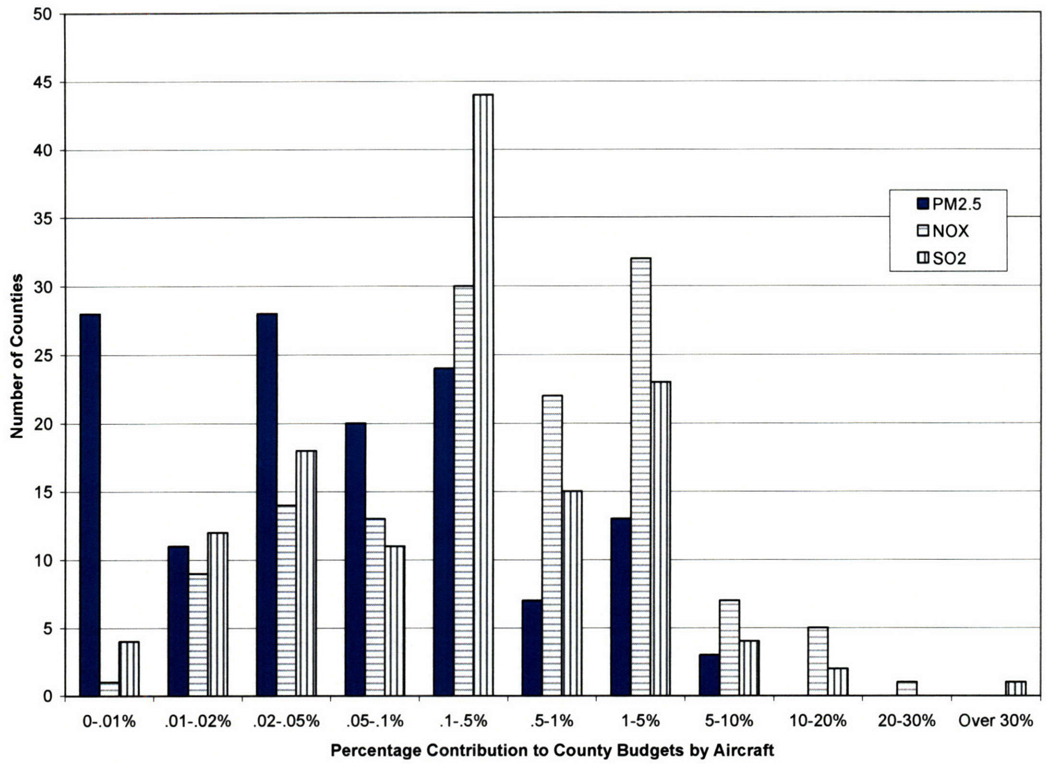

Figure 15. Percent contribution of aircraft to county emissions of primary $PM_{2.5}$ and $PM_{2.5}$ precursors, NO_X and SO_2.

Electric power generation accounts for 69% of U.S. SO_X emissions and 22% of NO_X emissions (*CAIR: Reducing Power Plant Emissions*, 2005). As these numbers fall due to CAIR, aircraft may play a more important role in county emissions of these pollutants. Projected reductions with CAIR are depicted in Figure 16.

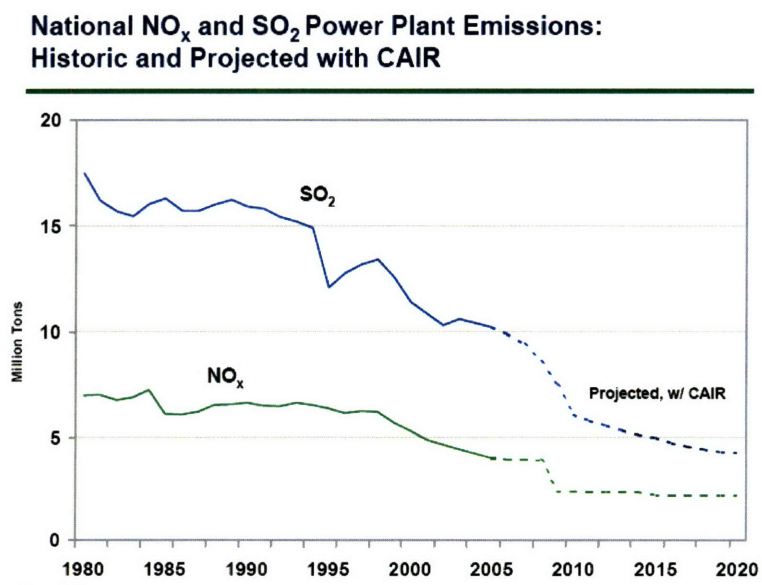

Figure 16. Projected Reductions with CAIR (*Clean Air Interstate Rule Where you Live*, 2007)

This preliminary assessment also highlights other important implications for the Energy Policy Act Study with the presence of ozone disbenefits. On a dollar basis, the benefits of PM reductions far outweigh the disbeneftis of ozone. Still, the effects of ozone are not negligible, and study participants must consider the potential costs of increased ozone levels around urban cores. While it is important to remember that the control case for this analysis included no aircraft emissions, an unrealistic scenario, benefit analysis results highlight the need to take into account the potential for such effects. While policy recommendations may include initiatives fully aligned with energy goals of the aviation sector, improvement in ground level ozone are not guaranteed.

The Ozone Transport Assessment Group (OTAG), a partnership between the U.S. EPA Environmental Council of the States (ECOS) and a number of industry and environmental groups, issued policy recommendations as to how to deal with ozone disbenefits (Lopez, 1996). General strategy refinements included:

- Exemption of localized area from some portion of NO_X controls sufficient to address local problem but not of the scope to exacerbate regional ozone
- Allocation of NO_X budgets or growth limits to a broad enough geographic area to allow a more optimum location of controls within problem area(s) to reduce or prevent disbenefits
- Pursuit of a different local schedule of some or all NO_X controls to optimize local ozone chemistry response
- Requiring additional or substitute compensating controls locally

Ozone disbenefits may be one of the greatest environmental challenges to address when assessing the environmental implication of initiatives. The implications for the larger Energy Act Study require a critical view of the initiatives implemented at areas most likely to experience adverse effects

Proposals aimed at targeting the energy challenges of the aviation sector require an in depth assessment of the local air quality impacts. Assessing the impact of aircraft on county inventories and the resultant health effects is only the first step toward developing these policies. Studies like the Energy Policy Act Study ensure that decisions are not made without careful consideration and reaffirm a commitment to develop air transportation with appropriate respect for human health and welfare.

This thesis is a preliminary assessment and numerical results should not be cited or quoted. Due to known improvements already being implemented for the larger Energy Policy Act Study, the contribution of this thesis is to discuss methods rather than best estimate results. There are several limitations to the work described in this thesis, particularly the health impact analysis. Therefore, the primary contribution of this thesis is in providing a description of the methodologies that will be used later within a more comprehensive study.

References:

Abbey, D. E., Colome, S. D., Mills, P. K., Burchette, R., Beeson, W. L., & Tian, Y. (1993). Chronic Disease Associated with Long-Term Concentration os of Nitrogen Dioxide. *Journal of Exposure Analysis and Environmental Epidemiology, 3*(2), 181-202.

Abbey, D. E., Hwang, B. L., Burchette, R. J., Vancuren, T., & Mills, P. K. (1995). Estimated Long-Term Ambient Concentrations of PM(10) and Development of Respiratory Symptoms in a Nonsmoking Population. *Archives of Environmental Health, 50*(2), 139-152.

About the National Emission Inventory Database (2007). U.S. Environmental Protection Agency. Retrieved April 2, 2007, from the World Wide Web: http://www.epa.gov/air/data/neidb.html

Adams, P. F., Hendershot, G. E., & Marano, M. A. (1999). Current Estimates from the National Health Interview Survey, 1996. *Vital Health Statistics, 10*(200), 1-212.

Amar, P., Bornstein, R., Feldman, H., Jeffries, H., Steyn, D., Yamartino, R., & Zhang, Y. (2004). *Final Report Summary: December 2003 Peer Review of the CMAQ Model.*

Annex 16 to the Convention on International Civil Aviation. (1993). International Civil Aviation Organization.

Annex 16 to the Convention on International Civil Aviation International Standards and Practices Environmental Protection, (1993).

Bell, M., Dominici, F., & Samet, J. M. (2005). A Meta-Analysis of Time-Series Studies of Ozone and Mortality with Comparison to the National Morbidity Mortality Air Pollution Study. *Epidemiology with Discussion, 16*(436-445).

Bell, M. L., Samet, J. M., & Dominici, F. (2004). Ozone and Mortality: A Meta-Analysis of Time-Series Studies and Comparison to a Multi-City Study (The National Morbidity, Mortality, and Air Pollution Study. *Johns Hopkins University, Dept. of Biostatistics Working Papers.*

BenMAP Fact Sheet (2004). U.S. Environmental Protection Agency. Retrieved May 8, 2007, 2007, from the World Wide Web: http://earth1.epa.gov/ttn/ecas/models/benmapfactsheet.pdf

Burnett, R. T., Smith-Doiron, M., Stieb, D., Raizenne, M. E., Brook, J. R., Dales, R. E., Leech, J. A., Cakmak, S., & Krewski, D. (2001). Association between Ozone and Hospitalization for Acute Respiratory Disease in Children less than 2 Years of Age. *American Journal of Epidemiology, 153*, 444-452.

Byun, D. W., & Ching, J. K. S. (Eds.). (1999). *Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System.* Research Triangle Park, NC: National Exposure Research Laboratory.

Calvert, J. W. (2006). Revisions to Smoke Number Data in Emissions Datbank. *Gas Turbine Technologies.*

Champagne, D. L. (1971). *Standard Measurement of Aircraft Gas Turbine Exhaust Smoke* (71-GT-88): ASME.

Chen, L., Jennison, B. L., Yang, W., & Omaye, S. T. (2000). Elementary School Absenteeism and Air Pollution. *Inhalation Toxicology, 12*(11), 997-1016.

Clean Air Act Amendments, (1990).

Clean Air Interstate Rule (2007). EPA. Retrieved April 23, 2007, 2007, from the World Wide Web: http://www.epa.gov/interstateairquality/

Clean Air Interstate Rule (CAIR): Reducing Power Plant Emissions for Cleaner Air, Healthier People, and a Strong America. (2005). EPA Office of Air and Radiation.

Clean Air Interstate Rule Where you Live (2007). US Environmental Protection Agency. Retrieved April 11, 2007, 2007, from the World Wide Web: http://www.epa.gov/CAIR/where.html

Cocker, T. D., & Horst, R. L. J. (1981). Hours of Work, Labor Productivity, and Environmental Conditions: A Case Study. *The Review of Economics and Statistics, 63*, 361-368.

Cody, R. P., Weisel, C. P., Birnbaum, G., & Lioy, P. J. (1992). The Effect of Ozone Associated with Summertime Photochemical Smog on the Frequency of Asthma Visits to Hospital Emergency Departments. *Environmental Research, 58*(2), 184-194.

Cropper, M. L., & Krupnick, A. J. (1990). *The Social Costs of Chronic Heart and Lung Disease* (Discussion Paper QE 89-16-REV). Washington, DC.

Davidson, K. (2007). Endpoints and Studies Used to Calculate Total Monetized Health Benefits. In I. Waitz (Ed.).

Dockery, D. W., Pope, C. A., Xu, X. P., Spengler, J. D., Ware, J. H., Fay, M. E., Ferris, B. G., & Speizer, F. E. (1993). An Association between Air Pollution and Mortality in Six U.S. Cities. *New England Journal of Medicine, 329*(24), 1753-1759.

Dopelheuer, A., & Lecht, M. (1999, October 12-16, 1998). *Influence of Engine Performance on Emission Characteristics.* Paper presented at the Symposium on Gas Turbine Engine Combustion, Emissions and Alternative Fuels, Lisbon, Portugal.

Draft Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression-Ignition Engines Less than 30 Liters per Cylinder. (EPA420-D-07-001)(2007). US Environmental Protection Agency Office of Transportation and Air Quality, Assessment and Standards Division.

EPA Green Book (2007). U.S. Environmental Protection Agency. Retrieved March 8, 2007, 2007, from the World Wide Web: http://www.epa.gov/oar/oaqps/greenbk/mappm25.html

Eyers, C. (2005). *Improving the First Order Approximation (FOA) for Characterizing Particulate Matter Emissions from Aircraft Jet Engines.* Paper presented at the Alternative Emissions Methodology Task Group (AEMTG) Meeting, Rio De Janeiro, Brazil.

FAA. (2005). *Aviation and Emissions: A Primer*: Federal Aviation Administration Office of Environment and Energy.

Gillette, W. (2006). Commercial Airports in Nonattainment Areas Identified by FAA Voluntary Low Emissions (VALE) Program. In G. Ratliff (Ed.).

Gilliland, F. D., Berhane, K., Rappaport, E. B., Thomas, D. C., Avol, E., Gauderman, W. J., London, S. J., Margolis, H. G., McConnell, R., Islam, K. T., & Peters, J. M.

(2001). The Effects of Ambient Air Pollution on School Absenteeism due to Respiratory Illness. *Epidemiology, 12*(1), 43-54.

Graham, M., Cointin, R., & Thompson, T. (2006). Memorandum EPACT Initial APU Results. In W. Gillette (Ed.).

Grell, G., Dudhia, J., & Stauffer, D. (1994). *A Description of the Fifth Generation Penn State/NCA Mesoscale Model (MM5)* (NCAR/TN-389+STR): National Center for Atmospheric Research.

Hall, R., J., Stouffer, S., & Colket, M. (2004, June 14-17, 2004). *Modeling Soot Formation in a Stirred Reactor.* Paper presented at the ASME Turbo Expo 2004, Vienna, Austria.

Han, S. (2003). *Reduced-order Modeling for Trace Species in the Post-Combustion Flow Path and Effects of Technology Trends on Emissions.* Unpublished Master of Science Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Handbook of Aviation Fuel Properties, Third Edition. (635)(2004). Alpharetta, GA: Coordination Research Council, Inc.

Hanna, A., Arunachalam, S., Adelman, Z., Baek, B., & Holland, A. (2006). *Project Report: A Methodology to Relate Changes in Airport Emissions to County-wide Air Pollution Levels*: University of North Carolina, Carolina Environmental Program.

HCUPnet Healthcare Cost and Utilization Project (2000). Agency for Healthcare Research and Quality (AHRQ). Retrieved, from the World Wide Web: www.ahrq.gov/HCUPnet

Huang, Y., Dominici, F., & Bell, M. (2005). Bayesian Hierarchical Distributed Lag Models for Summer Ozone Exposure and Cardio-Respiratory Mortality. *Environmetrics, 16*, 547-562.

Hurley, C. (2005). Private Correspondence about FOA3 nvPM Methods. In C. Eyers (Ed.).

Hurley, C. D. (1993). *Smoke Measured inside a Gas Turbine Combustor.* Paper presented at the 29th Joint Propulsion Conference and Exhibit, Monterey.

Industrial Economics, Incorporated (IEc) (2006). *Final Report: Expanded Expert Judgment Assessment of the Concentration-Response Relationship between PM2.5 Exposure and Mortality*: EPA Office of Air Quality Planning and Standards.

Industrial Economics, Incorporated (IEc) (1994). Memorandum. In Office of Air and Radiation. Jim DeMocker, Office of Policy Analysis and Review, U.S. Environmental Protection Agency (Ed.).

Iovinelli, R. (2005). Memorandum: Use of the First Order Approximation (FOA) to Estimate Aircraft Engine Particulate Matter (PM) Emissions in NEPA Documents and Clean Air Act General Conformity Analyses. In C. E. N. D. Manager, APP-600 (Ed.).

Iovinelli, R. (2007). Personal Communication. In G. Ratliff (Ed.).

Ito, K. (2003). *Special Report: Associations of Particulate Matter Components with Daily Mortality and Morbidity in Detroit, Michigan.* Boston, MA: Health Effects Institute.

Ito, K., De Leon, S. F., & Lippmann, M. (2005). Associations between Ozone and Daily Mortality: Analysis and Meta-Analysis. *Epidemiology, 16*(4), 446-457.

Krupnick, A. J., & Cropper, M. L. (1992). The Effect of Information on Health Risk. *Journal of Risk and Uncertainty, 5*(2), 29-48.

Kugele, A., Jelinek, F., & Gaffal, R. (2005). *Aircraft Particulate Matter Emission Estimates through all Phases of Flight* (EEC/SEE/2005/0014): EUROCONTROL.

Laden, F., Schwartz, J., Speizer, F. E., & Dockery, D. W. (2006). Reduction of Fine Particulate Air Pollution and Mortality. *American Journal of Respiratory and Critical Care Medicine, 173*, 667-672.

Levy, J. I., Chemerynski, S. M., & Sarnat, J. A. (2005). Ozone Exposure and Mortality Risk: An Empirical Bayes Meta-Regression Analysis. *Epidemiology*.

Lobo, P., Hagen, D., & Whitefield, P. (2006, May 22, 2006). *Aircraft PM Emissions from the APEX2 Measurement Campaign.* Paper presented at the Cambridge Particle Meeting, Cambridge, UK.

Lopez, B. (1996). OTAG ISI Task Group: Criteria for Modeling & Strategy Refinement regarding NOX Disbenefits. In ECOS/OTAG Implementation Issues and the Criteria Evaluation Mini-workgroup (Ed.).

Lukachko, S. P., Waitz, I. A., Miake-Lye, R. C., & Brown, R. C. (2005, June 2005). *Engine Design and Operational Impacts on Particulate Matter Precursor Emissions.* Paper presented at the ASME Turbo Expo, to appear in the Journal of Engineering for Gas Turbines and Power, Reno-Tahoe, Nevada.

Moolgavkar, S. H. (2000). Air Pollution and Hospital Admissions for Diseases of the Circulatory System in Three U.S. Metropolitan Areas. *Journal of Air and Waste Management Association, 50*, 1199-1206.

Moolgavkar, S. H. (2003). *Special Report: Air Pollution and Daily Deaths and Hospital Admissions in Los Angeles and Cook Counties*. Boston, MA: Health Effects Institute.

Moolgavkar, S. H., Luebeck, E. G., & Anderson, E. L. (1997). Air Pollution and Hospital Admissions for Respiratory Causes in Minneapolis-St Paul and Birmingham. *Epidemiology, 8*, 364-370.

Mrozek, J. R., & Taylor, L. O. (2002). What Determines a Value of Life? A Meta-Analysis. *Journal of Policy Analysis and Management, 21*(2), 253-270.

National Health Interview Survey (NHIS) (2007). CDC National Center for Disease Statistics. Retrieved April 25, 2007, 2007, from the World Wide Web: http://www.cdc.gov/nchs/nhis.htm

National Hospital Discharge and Ambulatory Surgery Data (2007). National Center for Health Statistics. Retrieved April 23, 2007, 2007, from the World Wide Web: http://www.cdc.gov/nchs/about/major/hdasd/nhds.htm

Neumann, J. E., Dickie, M. T., & Unsworth, R. E. (1994). Linkage Between Health Effects Estimation and Morbidity Valuation in the Section 812 Analysis-Draft Valuation Document. In O. o. A. a. R. Jim DeMocker, Office of Policy Analysis and Review, U.S. Environmental Protection Agency (Ed.): Industrial Economics Incorporates (IEC).

Norris, G., YoungPong, S. N., Koenig, J. Q., Larson, T. V., Sheppard, L., & Stout, J. W. (1999). An Association between Fine Particles and Asthma Emergency Department Visits for Children in Seattle. *Environmental Health Perspectives, 107*(6), 489-493.

NOx Budget Trading Program, 2005 Program Compliance and Environmental Results. (EPA430-R-06-013)(2006). US Environmental Protection Agency Office of Air and Radiation, Office of Atmospheric Programs, Clean Air Markets Division.

Ohsfeldt, M., Thrasher, T., Waitz, I., Ratliff, G., Sequeira, C., Thompson, T., Graham, M., Cointin, R., Gillette, W., & Gupta, M. (2007). Quantifying the Relationship between Air Traffic Management Inefficiency, Fuel Burn, and Air Pollutant Emissions. *Air Traffic Management Seminar*.

Ostro, B. (1987). Air Pollution and Morbidity Revisited: A Specification Test. *Journal of Environmental Economics Management, 14*, 87-98.

Ostro, B., Lipsett, M., Mann, J., Braxton-Owens, H., & White, M. (2001). Air Pollution and Exacerbation of Asthma in African-American Children in Los Angeles. *Epidemiology, 12*(2), 200-208.

Ostro, B. D., & Rothschild, S. (1989). Air Pollution and Acute Respiratory Morbidity: An Observational Study of Multiple Pollutants. *Environmental Research, 50*(238-247).

Particulate Matter Charicterisation. (2007, February 5-16, 2007). Paper presented at the ICAO Committee on Aviation Environmental Protection Seventh Meeting, Montreal.

Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J., & McFarland, M. (1999). *Aviation and the Global Atmosphere*: Intergovernmental Panel on Climate Change.

Peters, A., & Dockery, D. W. (2001). Increased Particulate Air Pollution and the Triggering of Myocardial Infarction. *Circulation, 103*, 2810-2815.

Pope, C. A., Burnett, R. T., Thurston, G. D., Thun, M. J., Calle, E. E., Krewski, D., & Godleski, J. J. (2004). Cardiovascular Mortality and Long-term Exposure to Particulate Air Pollution. *Circulation, 109*, 71-77.

Pope, C. A., Thun, M. J., Namboodiri, M. M., Dockery, D. W., Evans, J. S., Speizer, F. E., & Heath, C. W., Jr. (1995). Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults. *American Jounal of Respiratory and Critical Care Medicine, 151*, 669-674.

Pope, C. A. I., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *Journal of the American Medical Association, 287*, 1132-1141.

Pope, C. A. I., Dockery, D. W., Spengler, J. D., & Raizenne, M. E. (1991). Respiratory Health and PM10 Pollution: A Daily Time Series Analysis. *American Reveiw of Respiratory Diseases, 144*, 668-674.

Preliminary Nonroad Landbased Diesel Engine Rule: Air Quality Estimation, Selected Health and Welfare Benefits Methods, and Benefit Analysis Results. (2003). Abt, Associates.

Ransom, M. R., & Pope, C. A. I. (1992). Elementary School Absences and PM(10) Pollution in Utah Valley. *Environmental Research, 58*(2), 204-219.

Regional Planning Organization (2007, March 6, 2007). U.S. Environmental Protection Agency. Retrieved April 27, 2007, from the World Wide Web: http://www.epa.gov/air/visibility/regional.html

Regulatory Announcement: New Emission Standards for New Commercial Aircraft Engines. (EPA420-F-05-015)(2005). United State Environmental Protection Agency Office of Transportation and Air Quality.

Regulatory Impact Analysis-Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements. (EPA420-R-99-023)(1999). U.S. Environmental Protection Agency.

Regulatory Impact Assessment PM Nation Ambient Air Quality Standards. (2006). U.S. Environmental Protection Agency.

Rosamond, W., Broda, G., Kawalec, E., Rywik, S., Pajak, A., Cooper, L., & Chambless, L. (1999). Comparison of Medical Care and Survival of Hospitalized Patients with Acute Myocardial Infarction in Poland and the United States. *American Journal of Cardiology, 83*, 1180-1185.

Rowe, R. D., & Chestnut, L. G. (1986). *Report to the US Environmental Protection Agency, Office of Policy Analysis: Oxidants and Asthmatics in Los Angeles: A Benefit Analysis-Executive Summary* (EPA-230-09-86-018). Washington D.C.: Energy and Resources Consultants, Inc.

Russell, M. W., Huses, D. M., Drowns, S., Hamel, E. C., & Hartz, S. C. (1998). Direct Medical Costs of Coronary Artery Disease in the United States. *American Journal of Cardiology, 81*(9), 1110-1115.

Schumann, U., Arnold, F., Busen, R., Curtius, J., Karcher, B., Kiender, A., Petzold, A., Schlager, H., Schroder, F., & Wohlfrom, K. H. (2001). *Influence of Fuel Sulfur on the Composition of Aircraft Exhaust Plumes: The Experiments SULFUR 1-7* (152). Wessling, Germany: Institut fur Physik der Atmosphare.

Schwartz, J. (1993). Particulate Air Pollution and Chronic Respiratory Disease. *Environmental Research, 62*, 7-13.

Schwartz, J. (1994a). Air Pollution and Hospital Admissions for the Elderly in Detroit, Michigan. *American Jounal of Respiratory and Critical Care Medicine, 150*(3), 648-655.

Schwartz, J. (1994b). PM(10) Ozone and Hospital Admissions for the Elderly in Minneapolis-St Paul Minnesota. *Archives of Environmental Health, 45*(5), 366-347.

Schwartz, J. (1995). Short Term Fluctuations in Air Pollution and Hospital Admissions of the Elderly for Respiratory Disease. *Thorax, 50*(5), 531-538.

Schwartz, J., Dockery, D. W., Neas, L. M., Wypij, D., Ware, J. H., Spengler, J. D., Koutrakis, P., Speizer, F. E., & Ferris, B. G. J. (1994). Acute Effects of Summer Air Pollution on Respiratory Symptom Reporting in Children. *American Journal of Respiratory and Critical Care Medicine, 150*(5 Pt.1), 1234-1242.

Schwartz, J., & Neas, L. M. (2000). Fine Particles are More Strongly Associated than Course Particles with Acute Respiratory Effects in Schoolchildren. *Epidemiology, 11*, 6-10.

Sheppard, L. (2003). *Special Report: Ambient Air Pollution and Nonelderly Asthma Hospital Admissions in Seattle, Washington, 1987-1994*. Boston, MA: Health Effects Institute.

Shogren, J. F., & Stamland, T. (2002). Skill and the Value of Life. *Journal of Political Economy, 110*(1168-1173).

Smith, D. H., Malone, D. C., Lawson, K. A., Okamoto, L. J., Battista, C., & Saunders, W. B. (1997). A National Estimate of the Economic Costs of Asthma. *American Jounal of Respiratory and Critical Care Medicine, 156*(3Pt.1), 787-793.

Stanford, R., McLaughlin, T., & Okamoto, L. J. (1999). The Cost of Asthma in the Emergency Department and Hospital. *American Jounal of Respiratory and Critical Care Medicine, 160*(1), 211-215.

Status Report on Proposed Methodology to Characterize Jet/Gas Turbine Engine PM Emissions. (2003). FAA Office of Environment and Energy.

Stieb, D. M., Burnett, R. T., Beveridge, R. C., & Brook, J. R. (1996). Association between Ozone and Asthma Emergency Department Visits in Saint John New Brunswick, Canada. *Environmental Health Perspectives, 104*(12), 1354-1360.

Summary Table of Gaseous and Particulate Emissions from Aircraft Engines. (1990). Aircraft Environmental Support Office.

Tarrason, L., Jonson, J. E., Berntsen, T. K., & Rypdal, K. (2004). *Study on Air Quality Impacts of Non-LTO Emissions from Aviation* (3). Oslo: Norwegian Meteorological Institute.

Timin, B. (2005, May 18-20, 2005). *Speciated Modeled Attainment Test (SMAT): What is it and why do we need it?* Paper presented at the 3rd Particulate Matter/Regional Haze/Ozone Modeling Workshop, New Orleans, LA.

Tolley, G. S., & et.al. (1986). *Final Report to the U.S. Environmental Protection Agency: Valuation and Reductions in Human Health Symptoms and Risk*: University of Chicago.

Tonnessen, G., Wang, Z., Omary, M., Chien, C.-J., Wang, Y., Morris, R., Kemball-Cook, S., Jia, Y., Lau, S., Koo, B., Adelman, Z., Holland, A., & Wallace, J. (2006). *Final Report Prepared for the Western Regional Air Partnership (WRAP) 2002 Visibility Model Performance Evaluation*: University of California at Riverside, Environ International Corporation, University of North Carolina at Chapel Hill.

Trends in Asthma Morbidity and Mortality. (2002). American Lung Association, Best Practices and Program Services, Epidemiology and Statistics Unit.

Trends in Morbidity and Mortality: Pneumonia, Influenza, and Acute Respiratory Conditions. (2002). American Lung Association, Best Practices and Program Services, Epidemiology and Statistics Unit.

Vedal, S., Petkau, J., White, R., & Blair, J. (1998). Acute Effects of Ambient Inhalable Particles in Asthmatic and Nonasthmatic Children. *American Journal of Respiratory and Critical Care Medicine, 157*(4), 1034-1043.

Viscusi, V. K., & Aldy, J. E. (2003). The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World. *Journal of Risk and Uncertainty, 27*(1), 5-76.

Viscusi, V. K., Magat, W. A., & Huber, J. (1991). Pricing Environmental Health Risks: Survey Assessments of Risk-Risk and Risk-Dollar Trade-Offs for Chronic Bronchitis. *Journal of Environmental Economics and Management, 21*(32-51).

Waitz, I., Townsend, J., Cutcher-Gershenfeld, J., Greitzer, E., & Kerrebrock, J. (2004). *Report to the United States Congress: Aviation and the Environment: A National Vision Statement, Framework for Goals and Recommended Actions*.

Wayson, R. L., Fleming, G. G., Kim, B., & Draper, J. *Derivation of a First Order Approximation of Particulate Matter from Aircraft* (69970).

Weisel, C. P., Cody, R. P., & Lioy, P. J. (1995). Relationship between Summertime Ambient Ozone Levels and Emergency Department Visits for Asthma in Central New Jersey. *Environmental Health Perspectives, 103*(2), 97-102.

Wey, C. C., Anderson, B. E., Hudgins, C., Wey, C., Li-Jones, X., Winstead, E., Thornhill, L. K., Lobo, P., Hagen, D., Whitefield, P., Yelvington, P. E., Herndon, S. C., Onasch, T. B., Miake-Lye, R. C., Wormhoudt, J., Knighton, W. B., Howard, R., Bryant, D., Corporan, E., Moses, C., Holve, D., & Dodds, W. (2006). *Aircraft Particle Emissions eXperiment (APEX)* (ARL-TR-3903): NASA/U.S. Army Research Laboratory.

Whyte, R. B. (1982). *Alternative Jet Engine Fuels* (181): AGARD Advisory Report.

Wittels, E. H., Hay, J. W., & Gotto, A. M. J. (1990). Medical Costs of Coronary Artery Disease in the United States. *American Journal of Cardiology*.

Woodruff, T. J., Grillo, J., & Schoendorf, K. C. (1997). The Relationship Between Selected Cases of Postneonatal Infant Mortality and Particulate Air Pollution in the United States. *Environmental Health Perspectives, 105*(6), 608-612.

Zanobetti, A., & Schwartz, J. (2005). The Effect of Particulate Air Pollution on Emergency Admissions for Myocardial Infarction: A Multicity Case-Crossover Analysis. *Environmental Health Perspectives, 113*, 978-982.

Appendix A: Public Law 109-58, Energy Policy Act of 2005

Section 753. Aviation Fuel Conservation and Emissions.

(a) In General.—Not later than 60 days after the date of enactment of this Act, the Administrator of the Federal Aviation Administration and the Administrator of the Environmental Protection Agency shall jointly initiate a study to identify—

1) the impact of aircraft emissions on air quality in nonattainment areas;
2) ways to promote fuel conservation measures for aviation to enhance fuel efficiency and reduce emissions; and
3) opportunities to reduce air traffic inefficiencies that increase fuel burn and emissions.

(b) Focus.--The study under subsection (a) shall focus on how air traffic management inefficiencies, such as aircraft idling at airports, result in unnecessary fuel burn and air emissions.

(c) Report.--Not later than 1 year after the date of the initiation of the study under subsection (a), the Administrator of the Federal Aviation Administration and the Administrator of the Environmental Protection Agency shall jointly submit to the Committee on Energy and Commerce and the Committee on Transportation and Infrastructure of the House of Representatives and the Committee on Environment and Public Works and the Committee on Commerce, Science, and Transportation of the Senate a report that—

1) describes the results of the study; and
2) includes any recommendations on ways in which unnecessary fuel use and emissions affecting air quality may be reduced--

   (A) without adversely affecting safety and security and increasing individual aircraft noise; and

   (B) while taking into account all aircraft emissions and the impact of those emissions on the human health.

(d) Risk Assessments.--Any assessment of risk to human health and the environment prepared by the Administrator of the Federal Aviation Administration or the Administrator of the Environmental Protection Agency to support the report in this section shall be based on sound and objective scientific practices, shall consider the best available science, and shall present the weight of the scientific evidence concerning such risks.

Appendix B: National Ambient Air Quality Standards

Pollutant	Primary Stds.	Averaging Times	Secondary Stds.
Carbon Monoxide	9 ppm (10 mg/m^3)	8-hour(1)	None
	35 ppm (40 mg/m^3)	1-hour(1)	None
Lead	1.5 µg/m^3	Quarterly Average	Same as Primary
Nitrogen Dioxide	0.053 ppm (100 µg/m^3)	Annual (Arithmetic Mean)	Same as Primary
Particulate Matter (PM_{10})	Revoked(2)	Annual(2) (Arith. Mean)	
	150 µg/m^3	24-hour(3)	
Particulate Matter ($PM_{2.5}$)	15.0 µg/m^3	Annual(4) (Arith. Mean)	Same as Primary
	35 µg/m^3	24-hour(5)	
Ozone	0.08 ppm	8-hour(6)	Same as Primary
	0.12 ppm	1-hour(7) (Applies only in limited areas)	Same as Primary
Sulfur Oxides	0.03 ppm	Annual (Arith. Mean)	------
	0.14 ppm	24-hour(1)	-------
	-------	3-hour(1)	0.5 ppm (1300 µg/m^3)

(1) Not to be exceeded more than once per year.
(2) Due to a lack of evidence linking health problems to long-term exposure to coarse particle pollution, the agency revoked the annual PM10 standard in 2006 (effective December 17, 2006).
(3) Not to be exceeded more than once per year on average over 3 years.
(4) To attain this standard, the 3-year average of the weighted annual mean PM2.5 concentrations from single or multiple community-oriented monitors must not exceed 15.0 µg/m3.
(5) To attain this standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 35 µg/m3 (effective December 17, 2006).
(6) To attain this standard, the 3-year average of the fourth-highest daily maximum 8-hour average ozone concentrations measured at each monitor within an area over each year must not exceed 0.08 ppm.
(7) (a) The standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 ppm is < 1.
(b) As of June 15, 2005 EPA revoked the 1-hour ozone standard in all areas except the fourteen 8-hour ozone nonattainment Early Action Compact (EAC) Areas.

Appendix C: Members of the CAEP WG3 PM FOA Ad-Hoc Group

Roger Wayson	Volpe National Transportation Research Center
Ralph Iovinelli	US Federal Aviation Administration
Chris Eyers	QinetiQ
Chris Hurley	QinetiQ
Curtis Holsclaw	US Federal Aviation Administration
David Lee	Manchester Metropolitan University
David Lister	UK Civil Aviation Administration
Dom Sepulveda	Pratt-Whitney
John Rohde	National Aeronautics and Space Administration
Paul Madden	Rolls-Royce
Anuj Bhargava	Pratt-Whitney
Rick Miake-Lye	Aerodyne Research, Inc.
Will Dodd	General Electric
Chowen Wey	National Aeronautics and Space Administration

Appendix D: Commercial Aircraft Contributions to Nonattainment County Budgets by Airport

Airport Name	Airport Code	County	State	%CO	%NO_X	%SO_2	%VOC	%$PM_{2.5}$	%PM_{10}
Lehigh Valley International	ABE	LEHIGH	PA	0.44%	0.37%	0.26%	0.41%	0.06%	0.01%
Albuquerque International Sunport	ABQ	BERNALILLO	NM	0.72%	1.27%	2.55%	0.45%	0.05%	0.01%
Atlantic City International	ACY	ATLANTIC	NJ	1.05%	0.66%	0.99%	0.19%	0.04%	0.02%
Albany International	ALB	ALBANY	NY	0.39%	0.70%	0.11%	0.41%	0.08%	0.02%
Ted Stevens Anchorage International	ANC	ANCHORAGE	AK	3.93%	11.95%	7.30%	4.13%	0.91%	0.22%
Altoona-Blair County	AOO	BLAIR	PA	0.31%	0.01%	0.01%	0.13%	0.00%	0.00%
Aspen-Pitkin Co/Sardy Field	ASE	PITKIN	CO	1.65%	4.38%	7.51%	0.57%	0.53%	0.10%
Hartsfield-Jackson Atlanta International	ATL	FULTON	GA	9.25%	26.81%	36.36%	6.12%	6.04%	1.12%
Wilkes-Barre/Scranton Intl	AVP	LUZERNE	PA	0.34%	0.13%	0.08%	0.22%	0.03%	0.01%
Kalamazoo/Battle Creek International	AZO	KALAMAZOO	MI	0.29%	0.22%	0.16%	0.16%	0.04%	0.01%
Bradley International	BDL	HARTFORD	CT	0.44%	1.63%	1.00%	0.38%	0.17%	0.05%
Boeing Field/King County International	BFI	KING	WA	0.22%	0.12%	0.18%	0.16%	0.02%	0.01%
Meadows Field	BFL	KERN	CA	0.27%	0.02%	0.08%	0.02%	0.00%	0.00%
Hancock County-Bar Harbor	BHB	HANCOCK	ME	0.36%	0.10%	0.07%	0.09%	0.01%	0.00%
Birmingham International	BHM	JEFFERSON	AL	0.23%	0.24%	0.05%	0.20%	0.02%	0.01%
Billings Logan Intl	BIL	YELLOWSTONE	MT	1.38%	0.40%	0.05%	0.30%	0.02%	0.00%
Scott AFB/Midamerica	BLV	ST CLAIR	IL	0.27%	0.29%	0.22%	0.21%	0.01%	0.00%
Nashville International	BNA	DAVIDSON	TN	0.51%	1.51%	0.68%	0.63%	0.26%	0.05%
Boise Air Terminal/Gowen Field	BOI	ADA	ID	0.63%	0.77%	1.39%	0.26%	0.03%	0.01%
General Edward Lawrence Logan Intl	BOS	SUFFOLK	MA	2.66%	7.85%	3.90%	2.73%	0.84%	0.34%
Southeast Texas Regional	BPT	JEFFERSON	TX	0.36%	0.01%	0.00%	0.06%	0.00%	0.00%
Bert Mooney	BTM	SILVER BOW	MT	0.86%	0.21%	0.81%	0.06%	0.03%	0.00%
Buffalo Niagara Intl	BUF	ERIE	NY	0.20%	0.55%	0.06%	0.20%	0.04%	0.01%
Bob Hope	BUR	LOS ANGELES	CA	0.09%	0.09%	0.11%	0.04%	0.02%	0.00%
Baltimore-Washington International	BWI	ANNE ARUNDEL	MD	0.88%	2.81%	0.20%	0.98%	0.27%	0.13%
Columbia Metropolitan	CAE	LEXINGTON	SC	0.80%	0.84%	0.18%	0.45%	0.09%	0.02%
Akron-Canton Regional	CAK	SUMMIT	OH	0.37%	0.31%	0.08%	0.26%	0.06%	0.01%
Lovell Field	CHA	HAMILTON	TN	0.51%	0.17%	0.13%	0.30%	0.03%	0.01%

Chico Municipal	CIC	BUTTE	CA	0.37%	0.02%	0.02%	0.02%	0.00%	0.00%
Cleveland-Hopkins Intl	CLE	CUYAHOGA	OH	0.29%	1.28%	0.69%	0.56%	0.22%	0.08%
Charlotte/Douglas International	CLT	MECKLENBURG	NC	1.20%	4.70%	4.90%	1.56%	0.30%	0.09%
Port Columbus Intl	CMH	FRANKLIN	OH	0.31%	0.89%	1.05%	0.47%	0.12%	0.02%
City of Colorado Springs Muni	COS	EL PASO	CO	0.50%	0.40%	0.11%	0.25%	0.02%	0.01%
McClellan-Palomar	CRQ	SAN DIEGO	CA	0.15%	0.02%	0.05%	0.04%	0.00%	0.00%
Yeager	CRW	KANAWHA	WV	0.52%	0.09%	0.02%	0.29%	0.02%	0.01%
Cincinnati/No. Kentucky International	CVG	BOONE	KY	5.17%	6.76%	0.98%	6.44%	1.03%	0.29%
Dallas Love Field	DAL	DALLAS	TX	0.28%	0.35%	0.20%	0.33%	0.03%	0.01%
James M Cox Dayton Intl	DAY	MONTGOMERY	OH	0.50%	0.92%	0.31%	0.48%	0.13%	0.02%
Ronald Reagan Washington National	DCA	ARLINGTON	VA	3.08%	13.54%	11.57%	3.29%	1.61%	0.48%
Denver International	DEN	DENVER	CO	1.83%	7.41%	3.35%	2.90%	1.24%	0.32%
Dallas-Fort Worth International	DFW	TARRANT	TX	1.27%	5.68%	3.82%	1.17%	0.40%	0.07%
Duluth International	DLH	ST LOUIS	MN	0.25%	0.04%	0.03%	0.02%	0.01%	0.00%
Detroit Metropolitan-Wayne County	DTW	WAYNE	MI	0.45%	1.77%	0.37%	1.08%	0.40%	0.24%
Ellington Field	EFD	HARRIS	TX	0.08%	0.00%	0.01%	0.04%	0.00%	0.00%
El Paso International	ELP	EL PASO	TX	0.34%	0.81%	0.53%	0.26%	0.07%	0.01%
Erie International/Tom Ridge Field	ERI	ERIE	PA	0.21%	0.07%	0.04%	0.15%	0.02%	0.00%
Evansville Regional	EVV	VANDERBURGH	IN	0.64%	0.25%	0.19%	0.34%	0.03%	0.00%
Newark Liberty Intl	EWR	ESSEX	NJ	2.79%	11.16%	7.44%	3.76%	3.18%	1.34%
Fairbanks International	FAI	FAIRBANKS	AK	0.40%	0.86%	0.16%	0.30%	0.01%	0.00%
Fresno Yosemite International	FAT	FRESNO	CA	0.45%	0.10%	0.14%	0.05%	0.01%	0.00%
Fayetteville Regional/Grannis Field	FAY	CUMBERLAND	NC	0.24%	0.10%	0.14%	0.09%	0.03%	0.01%
Bishop International	FNT	GENESEE	MI	0.25%	0.33%	0.46%	0.26%	0.06%	0.01%
Spokane International	GEG	SPOKANE	WA	0.31%	0.69%	1.19%	0.14%	0.03%	0.01%
Groton-New London	GON	NEW LONDON	CT	0.65%	0.07%	0.02%	0.12%	0.00%	0.00%
Gerald R. Ford International	GRR	KENT	MI	0.31%	0.57%	0.38%	0.30%	0.07%	0.01%
Piedmont Triad International	GSO	GUILFORD	NC	0.39%	0.72%	1.03%	0.27%	0.11%	0.03%
Greenville-Spartanburg International	GSP	GREENVILLE	SC	0.34%	0.57%	0.49%	0.21%	0.05%	0.01%
Hagerstown Regional-Richard Henson Field	HGR	WASHINGTON	MD	0.50%	0.02%	0.01%	0.15%	0.00%	0.00%
Helena Regional	HLN	LEWIS AND CLARK	MT	0.97%	0.22%	0.77%	0.06%	0.02%	0.00%
Henderson Executive	HND	CLARK	NV	0.07%	0.00%	0.00%	0.01%	0.00%	0.00%
William P. Hobby	HOU	HARRIS	TX	0.16%	0.16%	0.09%	0.14%	0.02%	0.00%
Westchester Cty	HPN	WESTCHESTER	NY	0.36%	0.48%	0.50%	0.67%	0.16%	0.04%
Tri-State/Milton J. Ferguson Field	HTS	WAYNE	WV	1.53%	0.10%	0.21%	0.28%	0.03%	0.01%

Tweed-New Haven	HVN	NEW HAVEN	CT	0.14%	0.02%	0.01%	0.04%	0.00%	0.00%
Washington Dulles International	IAD	LOUDOUN	VA	3.60%	18.32%	19.55%	4.99%	1.48%	0.25%
George Bush Intercontinental	IAH	HARRIS	TX	0.37%	0.91%	0.48%	0.43%	0.09%	0.02%
Laughlin/Bullhead International	IFP	MOHAVE	AZ	0.10%	0.05%	0.18%	0.00%	0.00%	0.00%
Indianapolis International	IND	MARION	IN	0.55%	2.20%	0.19%	1.30%	0.15%	0.05%
Imperial County	IPL	IMPERIAL	CA	0.49%	0.01%	0.03%	0.01%	0.00%	0.00%
Long Island - MacArthur	ISP	SUFFOLK	NY	0.14%	0.19%	0.03%	0.08%	0.04%	0.01%
Inyokern	IYK	KERN	CA	0.08%	0.00%	0.01%	0.00%	0.00%	0.00%
John F. Kennedy Intl	JFK	QUEENS	NY	1.77%	9.01%	4.34%	1.44%	1.29%	0.58%
Chautauqua County/Jamestown	JHW	CHAUTAUQUA	NY	0.09%	0.02%	0.00%	0.03%	0.00%	0.00%
John Murtha Johnstown-Cambria Co	JST	CAMBRIA	PA	0.42%	0.02%	0.01%	0.13%	0.00%	0.00%
Capital City	LAN	CLINTON	MI	1.26%	0.77%	1.42%	0.79%	0.07%	0.01%
McCarran International	LAS	CLARK	NV	0.97%	2.72%	0.52%	0.33%	0.30%	0.07%
Los Angeles International	LAX	LOS ANGELES	CA	0.34%	1.30%	1.39%	0.29%	0.19%	0.06%
Arnold Palmer Regional	LBE	WESTMORELAND	PA	0.26%	0.03%	0.04%	0.16%	0.01%	0.00%
Brazoria County	LBX	BRAZORIA	TX	0.26%	0.01%	0.01%	0.03%	0.00%	0.00%
Rickenbacker International	LCK	FRANKLIN	OH	0.12%	0.22%	0.26%	0.31%	0.03%	0.01%
LaGuardia	LGA	QUEENS	NY	1.03%	3.50%	2.05%	0.86%	0.61%	0.27%
Long Beach/Daugherty Field	LGB	LOS ANGELES	CA	0.12%	0.06%	0.06%	0.03%	0.01%	0.00%
Klamath Falls	LMT	KLAMATH	OR	0.19%	0.07%	0.15%	0.01%	0.00%	0.00%
Merced Municipal/MacReady Field	MCE	MERCED	CA	0.17%	0.00%	0.02%	0.03%	0.00%	0.00%
Middle Georgia Regional	MCN	BIBB	GA	0.30%	0.05%	0.04%	0.11%	0.01%	0.00%
Harrisburg Intl	MDT	DAUPHIN	PA	0.43%	0.60%	0.70%	0.62%	0.13%	0.02%
Chicago Midway International	MDW	COOK	IL	0.17%	0.53%	0.33%	0.24%	0.13%	0.05%
Memphis International	MEM	SHELBY	TN	1.11%	3.67%	0.78%	2.77%	0.66%	0.16%
Rogue Valley International - Medford	MFR	JACKSON	OR	0.09%	0.11%	0.12%	0.02%	0.00%	0.00%
Manchester	MHT	HILLSBOROUGH	NH	0.40%	1.82%	1.05%	0.37%	0.09%	0.03%
General Mitchell International	MKE	MILWAUKEE	WI	0.46%	1.45%	0.24%	0.74%	0.09%	0.04%
Muskegon County	MKG	MUSKEGON	MI	0.33%	0.02%	0.01%	0.20%	0.00%	0.00%
Modesto City-County-Harry Sham Field	MOD	STANISLAUS	CA	0.36%	0.02%	0.03%	0.03%	0.00%	0.00%
Merrill Field	MRI	ANCHORAGE	AK	0.48%	0.01%	0.01%	0.11%	0.00%	0.00%
Northwest Alabama Regional Airport	MSL	COLBERT	AL	0.88%	0.01%	0.00%	0.06%	0.00%	0.00%
Dane County Regional-Truax Field	MSN	DANE	WI	0.37%	0.47%	0.13%	0.23%	0.03%	0.01%
Minneapolis-St Paul Intl/Wold-Chamb	MSP	HENNEPIN	MN	0.75%	2.61%	1.33%	1.47%	0.60%	0.18%
Metropolitan Oakland International	OAK	ALAMEDA	CA	0.96%	2.03%	1.56%	0.87%	0.27%	0.09%

Ontario International	ONT	SAN BERNARDINO	CA	0.23%	0.47%	1.44%	0.07%	0.05%	0.01%
Chicago O'Hare International	ORD	COOK	IL	0.80%	2.63%	1.86%	0.70%	0.46%	0.17%
Norfolk International	ORF	NORFOLK	VA	0.85%	0.77%	0.64%	1.00%	0.16%	0.06%
Oxnard	OXR	VENTURA	CA	0.37%	0.01%	0.03%	0.02%	0.00%	0.00%
Portland Intl	PDX	MULTNOMAH	OR	0.45%	1.47%	1.40%	0.31%	0.08%	0.04%
Newport News/Williamsburg International	PHF	NEWPORT NEWS	VA	1.68%	0.45%	0.31%	0.65%	0.09%	0.03%
Philadelphia Intl	PHL	PHILADELPHIA	PA	3.10%	5.72%	1.42%	3.97%	1.08%	0.36%
Phoenix Sky Harbor International	PHX	MARICOPA	AZ	0.40%	1.85%	5.14%	0.22%	0.21%	0.04%
Pocatello Regional	PIH	POWER	ID	1.95%	0.20%	0.04%	0.11%	0.00%	0.00%
Pittsburgh International	PIT	ALLEGHENY	PA	0.37%	0.83%	0.14%	0.67%	0.12%	0.05%
Mid-Ohio Valley Regional	PKB	WOOD	WV	0.44%	0.04%	0.01%	0.17%	0.00%	0.00%
Northern Maine Regional	PQI	AROOSTOOK	ME	0.05%	0.01%	0.01%	0.00%	0.00%	0.00%
Pease International Tradeport	PSM	ROCKINGHAM	NH	0.30%	0.19%	0.03%	0.12%	0.00%	0.00%
Palm Springs International	PSP	RIVERSIDE	CA	0.15%	0.11%	0.21%	0.03%	0.02%	0.00%
Theodore Francis Green State	PVD	KENT	RI	0.93%	5.38%	3.76%	0.88%	0.94%	0.26%
Portland International Jetport	PWM	CUMBERLAND	ME	0.32%	0.42%	0.22%	0.19%	0.04%	0.02%
Reading Regional/Carl A Spaatz Fld	RDG	BERKS	PA	0.58%	0.02%	0.01%	0.15%	0.00%	0.00%
Raleigh-Durham International	RDU	WAKE	NC	0.50%	1.74%	2.54%	0.58%	0.14%	0.03%
Richmond International	RIC	HENRICO	VA	0.73%	1.72%	1.56%	1.04%	0.19%	0.05%
Knox County Regional	RKD	KNOX	ME	0.87%	0.06%	0.05%	0.26%	0.01%	0.00%
Reno/Tahoe International	RNO	WASHOE	NV	0.70%	1.74%	0.74%	0.19%	0.09%	0.01%
Roanoke Regional/ Woodrum Field	ROA	ROANOKE	VA	2.46%	1.45%	1.46%	1.17%	0.04%	0.03%
Greater Rochester Int'l	ROC	MONROE	NY	0.28%	0.59%	0.06%	0.26%	0.05%	0.01%
San Diego International	SAN	SAN DIEGO	CA	0.22%	0.93%	1.14%	0.10%	0.06%	0.02%
San Antonio International	SAT	BEXAR	TX	0.25%	0.50%	0.14%	0.35%	0.04%	0.01%
Stockton Metropolitan	SCK	SAN JOAQUIN	CA	0.33%	0.04%	0.06%	0.06%	0.01%	0.00%
Louisville International-Standiford Fiel	SDF	JEFFERSON	KY	0.75%	1.21%	0.21%	2.50%	0.20%	0.07%
Seattle-Tacoma International	SEA	KING	WA	0.21%	1.64%	2.07%	0.23%	0.23%	0.08%
San Francisco International	SFO	SAN MATEO	CA	2.07%	8.78%	9.33%	1.95%	1.16%	0.34%
Sheridan County	SHR	SHERIDAN	WY	0.98%	0.05%	0.11%	0.08%	0.00%	0.00%
Norman Y. Mineta San Jose International	SJC	SANTA CLARA	CA	0.36%	1.20%	1.00%	0.30%	0.13%	0.03%
Salt Lake City International	SLC	SALT LAKE	UT	0.80%	2.90%	2.30%	0.91%	0.46%	0.12%
Sacramento International	SMF	SACRAMENTO	CA	0.43%	1.26%	1.58%	0.31%	0.14%	0.04%
John Wayne Airport-Orange County	SNA	ORANGE	CA	0.43%	0.73%	0.68%	0.26%	0.19%	0.04%
Lambert-St Louis International	STL	ST LOUIS CITY	MO	0.29%	1.07%	0.34%	0.42%	0.13%	0.02%

Stewart International	SWF	ORANGE	NY	0.36%	0.29%	0.03%	0.26%	0.02%	0.00%
Syracuse-Hancock Intl	SYR	ONONDAGA	NY	0.38%	0.71%	0.26%	0.29%	0.07%	0.01%
Toledo Express	TOL	LUCAS	OH	0.54%	0.38%	0.14%	0.50%	0.08%	0.02%
Tri-Cities Regional TN/VA	TRI	SULLIVAN	TN	0.77%	0.09%	0.02%	0.26%	0.02%	0.01%
Trenton Mercer	TTN	MERCER	NJ	0.52%	0.06%	0.02%	0.38%	0.03%	0.01%
Tucson International	TUS	PIMA	AZ	0.75%	0.95%	0.43%	0.06%	0.03%	0.01%
McGhee-Tyson	TYS	BLOUNT	TN	1.09%	1.93%	0.32%	0.87%	0.08%	0.03%
University Park	UNV	CENTRE	PA	0.52%	0.08%	0.04%	0.15%	0.01%	0.00%
Southern California Logistics	VCV	SAN BERNARDINO	CA	0.22%	0.01%	0.05%	0.01%	0.00%	0.00%
North Las Vegas	VGT	CLARK	NV	0.25%	0.01%	0.00%	0.04%	0.00%	0.00%
Visalia Municipal	VIS	TULARE	CA	0.03%	0.01%	0.01%	0.01%	0.00%	0.00%
Westerly State	WST	WASHINGTON	RI	0.16%	0.01%	0.01%	0.04%	0.00%	0.00%
Yakima Air Terminal/McAllister	YKM	YAKIMA	WA	0.24%	0.06%	0.22%	0.06%	0.00%	0.00%
Youngstown-Warren Regional	YNG	TRUMBULL	OH	0.42%	0.04%	0.01%	0.26%	0.00%	0.00%
Yuma MCAS-Yuma International	YUM	YUMA	AZ	0.97%	0.09%	0.37%	0.03%	0.01%	0.00%

Appendix E: Commercial Aircraft Contributions to Nonattainment County Budgets by County

County Federal Information Processing Code (CoFIPS)	County	Airport Code	CO	NO_X	SO_X	VOC	$PM_{2.5}$	PM_{10}
01033	COLBERT	MSL	0.88%	0.01%	0.00%	0.06%	0.00%	0.00%
01073	JEFFERSON	BHM	0.23%	0.24%	0.05%	0.20%	0.02%	0.01%
02020	ANCHORAGE	ANC/MRI	4.41%	11.96%	7.32%	4.24%	0.91%	0.22%
02090	FAIRBANKS	FAI	0.40%	0.86%	0.16%	0.30%	0.01%	0.00%
04013	MARICOPA	PHX	0.40%	1.85%	5.14%	0.22%	0.21%	0.04%
04015	MOHAVE	IFP	0.10%	0.05%	0.18%	0.00%	0.00%	0.00%
04019	PIMA	TUS	0.75%	0.95%	0.43%	0.06%	0.03%	0.01%
04027	YUMA	YUM	0.97%	0.09%	0.37%	0.03%	0.01%	0.00%
06001	ALAMEDA	OAK	0.96%	2.03%	1.56%	0.87%	0.27%	0.09%
06007	BUTTE	CIC	0.37%	0.02%	0.02%	0.02%	0.00%	0.00%
06019	FRESNO	FAT	0.45%	0.10%	0.14%	0.05%	0.01%	0.00%
06025	IMPERIAL	IPL	0.49%	0.01%	0.03%	0.01%	0.00%	0.00%
06029	KERN	BFL/IYK	0.35%	0.02%	0.09%	0.03%	0.00%	0.00%
06037	LOS ANGELES	BUR/LAX/LGB	0.55%	1.45%	1.56%	0.37%	0.21%	0.07%
06047	MERCED	MCE	0.17%	0.00%	0.02%	0.03%	0.00%	0.00%
06059	ORANGE	SNA	0.43%	0.73%	0.68%	0.26%	0.19%	0.04%
06065	RIVERSIDE	PSP	0.15%	0.11%	0.21%	0.03%	0.02%	0.00%
06067	SACRAMENTO	SMF	0.43%	1.26%	1.58%	0.31%	0.14%	0.04%
06071	SAN BERNARDINO	ONT/VCV	0.45%	0.49%	1.49%	0.07%	0.05%	0.01%
06073	SAN DIEGO	CRQ/SAN	0.37%	0.95%	1.19%	0.14%	0.07%	0.02%
06077	SAN JOAQUIN	SCK	0.33%	0.04%	0.06%	0.06%	0.01%	0.00%
06081	SAN MATEO	SFO	2.07%	8.78%	9.33%	1.95%	1.16%	0.34%
06085	SANTA CLARA	SJC	0.36%	1.20%	1.00%	0.30%	0.13%	0.03%
06099	STANISLAUS	MOD	0.36%	0.02%	0.03%	0.03%	0.00%	0.00%

06107	TULARE	VIS	0.03%	0.01%	0.01%	0.01%	0.00%	0.00%
06111	VENTURA	OXR	0.37%	0.01%	0.03%	0.02%	0.00%	0.00%
08031	DENVER	DEN	1.83%	7.41%	3.35%	2.90%	1.24%	0.32%
08041	EL PASO	COS	0.50%	0.40%	0.11%	0.25%	0.02%	0.01%
08097	PITKIN	ASE	1.65%	4.38%	7.51%	0.57%	0.53%	0.10%
09003	HARTFORD	BDL	0.44%	1.63%	1.00%	0.38%	0.17%	0.05%
09009	NEW HAVEN	HVN	0.14%	0.02%	0.01%	0.04%	0.00%	0.00%
09011	NEW LONDON	GON	0.65%	0.07%	0.02%	0.12%	0.00%	0.00%
13021	BIBB	MCN	0.30%	0.05%	0.04%	0.11%	0.01%	0.00%
13063	FULTON	ATL	9.25%	26.81%	36.36%	6.12%	6.04%	1.12%
16001	ADA	BOI	0.63%	0.77%	1.39%	0.26%	0.03%	0.01%
16077	POWER	PIH	1.95%	0.20%	0.04%	0.11%	0.00%	0.00%
17031	COOK	MDW/ORD	1.06%	3.16%	2.19%	0.94%	0.59%	0.21%
17163	ST CLAIR	BLV	0.27%	0.29%	0.22%	0.21%	0.01%	0.00%
18097	MARION	IND	0.55%	2.20%	0.19%	1.30%	0.15%	0.05%
18163	VANDERBURGH	EVV	0.64%	0.25%	0.19%	0.34%	0.03%	0.00%
21015	BOONE	CVG	5.17%	6.76%	0.98%	6.44%	1.03%	0.29%
21111	JEFFERSON	SDF	0.75%	1.21%	0.21%	2.50%	0.20%	0.07%
23003	AROOSTOOK	PQI	0.05%	0.01%	0.01%	0.00%	0.00%	0.00%
23005	CUMBERLAND	PWM	0.32%	0.42%	0.22%	0.19%	0.04%	0.02%
23009	HANCOCK	BHB	0.36%	0.10%	0.07%	0.09%	0.01%	0.00%
23013	KNOX	RKD	0.87%	0.06%	0.05%	0.26%	0.01%	0.00%
24003	ANNE ARUNDEL	BWI	0.88%	2.81%	0.20%	0.98%	0.27%	0.13%
24043	WASHINGTON	HGR	0.50%	0.02%	0.01%	0.15%	0.00%	0.00%
25025	SUFFOLK	BOS	2.66%	7.85%	3.90%	2.73%	0.84%	0.34%
26037	CLINTON	LAN	1.26%	0.77%	1.42%	0.79%	0.07%	0.01%
26049	GENESEE	FNT	0.25%	0.33%	0.46%	0.26%	0.06%	0.01%
26077	KALAMAZOO	AZO	0.29%	0.22%	0.16%	0.16%	0.04%	0.01%
26081	KENT	GRR	0.31%	0.57%	0.38%	0.30%	0.07%	0.01%
26121	MUSKEGON	MKG	0.33%	0.02%	0.01%	0.20%	0.00%	0.00%
26163	WAYNE	DTW	0.45%	1.77%	0.37%	1.08%	0.40%	0.24%
27053	HENNEPIN	MSP	0.75%	2.61%	1.33%	1.47%	0.60%	0.18%
27137	ST LOUIS	DLH	0.25%	0.04%	0.03%	0.02%	0.01%	0.00%
29189	ST LOUIS CITY	STL	0.29%	1.07%	0.34%	0.42%	0.13%	0.02%
30049	LEWIS AND CLARK	HLN	0.97%	0.22%	0.77%	0.06%	0.02%	0.00%

30093	SILVER BOW	BTM	0.86%	0.21%	0.81%	0.06%	0.03%	0.00%
30111	YELLOWSTONE	BIL	1.38%	0.40%	0.05%	0.30%	0.02%	0.00%
32003	CLARK	HND/LAS/VGT	1.30%	2.73%	0.52%	0.38%	0.30%	0.07%
32031	WASHOE	RNO	0.70%	1.74%	0.74%	0.19%	0.09%	0.01%
33011	HILLSBOROUGH	MHT	0.40%	1.82%	1.05%	0.37%	0.09%	0.03%
33015	ROCKINGHAM	PSM	0.30%	0.19%	0.03%	0.12%	0.00%	0.00%
34001	ATLANTIC	ACY	1.05%	0.66%	0.99%	0.19%	0.04%	0.02%
34013	ESSEX	EWR	2.79%	11.16%	7.44%	3.76%	3.18%	1.34%
34021	MERCER	TTN	0.52%	0.06%	0.02%	0.38%	0.03%	0.01%
35001	BERNALILLO	ABQ	0.72%	1.27%	2.55%	0.45%	0.05%	0.01%
36001	ALBANY	ALB	0.39%	0.70%	0.11%	0.41%	0.08%	0.02%
36013	CHAUTAUQUA	JHW	0.09%	0.02%	0.00%	0.03%	0.00%	0.00%
36029	ERIE	BUF	0.20%	0.55%	0.06%	0.20%	0.04%	0.01%
36055	MONROE	ROC	0.28%	0.59%	0.06%	0.26%	0.05%	0.01%
36067	ONONDAGA	SYR	0.38%	0.71%	0.26%	0.29%	0.07%	0.01%
36071	ORANGE	SWF	0.36%	0.29%	0.03%	0.26%	0.02%	0.00%
36081	QUEENS	JFK/LGA	2.79%	12.51%	6.39%	2.30%	1.90%	0.85%
36103	SUFFOLK	ISP	0.14%	0.19%	0.03%	0.08%	0.04%	0.01%
36119	WESTCHESTER	HPN	0.36%	0.48%	0.50%	0.67%	0.16%	0.04%
37051	CUMBERLAND	FAY	0.24%	0.10%	0.14%	0.09%	0.03%	0.01%
37081	GUILFORD	GSO	0.39%	0.72%	1.03%	0.27%	0.11%	0.03%
37119	MECKLENBURG	CLT	1.20%	4.70%	4.90%	1.56%	0.30%	0.09%
37183	WAKE	RDU	0.50%	1.74%	2.54%	0.58%	0.14%	0.03%
39035	CUYAHOGA	CLE	0.29%	1.28%	0.69%	0.56%	0.22%	0.08%
39049	FRANKLIN	CMH/LCK	0.43%	1.11%	1.31%	0.78%	0.15%	0.02%
39095	LUCAS	TOL	0.54%	0.38%	0.14%	0.50%	0.08%	0.02%
39113	MONTGOMERY	DAY	0.50%	0.92%	0.31%	0.48%	0.13%	0.02%
39153	SUMMIT	CAK	0.37%	0.31%	0.08%	0.26%	0.06%	0.01%
39155	TRUMBULL	YNG	0.42%	0.04%	0.01%	0.26%	0.00%	0.00%
41029	JACKSON	MFR	0.09%	0.11%	0.12%	0.02%	0.00%	0.00%
41035	KLAMATH	LMT	0.19%	0.07%	0.15%	0.01%	0.00%	0.00%
41051	MULTNOMAH	PDX	0.45%	1.47%	1.40%	0.31%	0.08%	0.04%
42003	ALLEGHENY	PIT	0.37%	0.83%	0.14%	0.67%	0.12%	0.05%
42011	BERKS	RDG	0.58%	0.02%	0.01%	0.15%	0.00%	0.00%
42013	BLAIR	AOO	0.31%	0.01%	0.01%	0.13%	0.00%	0.00%

42021	CAMBRIA	JST	0.42%	0.02%	0.01%	0.13%	0.00%	0.00%
42027	CENTRE	UNV	0.52%	0.08%	0.04%	0.15%	0.01%	0.00%
42043	DAUPHIN	MDT	0.43%	0.60%	0.70%	0.62%	0.13%	0.02%
42045	PHILADELPHIA	PHL	3.10%	5.72%	1.42%	3.97%	1.08%	0.36%
42049	ERIE	ERI	0.21%	0.07%	0.04%	0.15%	0.02%	0.00%
42077	LEHIGH	ABE	0.44%	0.37%	0.26%	0.41%	0.06%	0.01%
42079	LUZERNE	AVP	0.34%	0.13%	0.08%	0.22%	0.03%	0.01%
42129	WESTMORELAND	LBE	0.26%	0.03%	0.04%	0.16%	0.01%	0.00%
44003	KENT	PVD	0.93%	5.38%	3.76%	0.88%	0.94%	0.26%
44009	WASHINGTON	WST	0.16%	0.01%	0.01%	0.04%	0.00%	0.00%
45063	LEXINGTON	CAE	0.80%	0.84%	0.18%	0.45%	0.09%	0.02%
45083	GREENVILLE	GSP	0.34%	0.57%	0.49%	0.21%	0.05%	0.01%
47009	BLOUNT	TYS	1.09%	1.93%	0.32%	0.87%	0.08%	0.03%
47037	DAVIDSON	BNA	0.51%	1.51%	0.68%	0.63%	0.26%	0.05%
47065	HAMILTON	CHA	0.51%	0.17%	0.13%	0.30%	0.03%	0.01%
47157	SHELBY	MEM	1.11%	3.67%	0.78%	2.77%	0.66%	0.16%
47163	SULLIVAN	TRI	0.77%	0.09%	0.02%	0.26%	0.02%	0.01%
48029	BEXAR	SAT	0.25%	0.50%	0.14%	0.35%	0.04%	0.01%
48039	BRAZORIA	LBX	0.26%	0.01%	0.01%	0.03%	0.00%	0.00%
48113	DALLAS	DAL	0.28%	0.35%	0.20%	0.33%	0.03%	0.01%
48141	EL PASO	ELP	0.34%	0.81%	0.53%	0.26%	0.07%	0.01%
48201	HARRIS	EFD/HOU/IAH	0.62%	1.07%	0.57%	0.61%	0.11%	0.02%
48245	JEFFERSON	BPT	0.36%	0.01%	0.00%	0.06%	0.00%	0.00%
48439	TARRANT	DFW	1.27%	5.68%	3.82%	1.17%	0.40%	0.07%
49035	SALT LAKE	SLC	0.80%	2.90%	2.30%	0.91%	0.46%	0.12%
51013	ARLINGTON	DCA	3.08%	13.54%	11.57%	3.29%	1.61%	0.48%
51087	HENRICO	RIC	0.73%	1.72%	1.56%	1.04%	0.19%	0.05%
51107	LOUDOUN	IAD	3.60%	18.32%	19.55%	4.99%	1.48%	0.25%
51700	NEWPORT NEWS	PHF	1.68%	0.45%	0.31%	0.65%	0.09%	0.03%
51710	NORFOLK	ORF	0.85%	0.77%	0.64%	1.00%	0.16%	0.06%
51770	ROANOKE	ROA	2.46%	1.45%	1.46%	1.17%	0.04%	0.03%
53033	KING	BFI/SEA	0.43%	1.76%	2.25%	0.40%	0.24%	0.09%
53063	SPOKANE	GEG	0.31%	0.69%	1.19%	0.14%	0.03%	0.01%
53077	YAKIMA	YKM	0.24%	0.06%	0.22%	0.06%	0.00%	0.00%
54039	KANAWHA	CRW	0.52%	0.09%	0.02%	0.29%	0.02%	0.01%

54099	WAYNE	HTS	1.53%	0.10%	0.21%	0.28%	0.03%	0.01%
54107	WOOD	PKB	0.44%	0.04%	0.01%	0.17%	0.00%	0.00%
55025	DANE	MSN	0.37%	0.47%	0.13%	0.23%	0.03%	0.01%
55079	MILWAUKEE	MKE	0.46%	1.45%	0.24%	0.74%	0.09%	0.04%
56033	SHERIDAN	SHR	0.98%	0.05%	0.11%	0.08%	0.00%	0.00%