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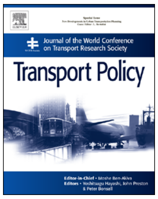

Assessing the impact of aviation environmental policies on public health

Elza Brunelle-Yeung[a], Tudor Masek[a], Julien J. Rojo[a], Jonathan I. Levy[b], Saravanan Arunachalam[c], Sondra M. Miller[d], Steven R.H. Barrett[e,1], Stephen R. Kuhn[a], Ian A. Waitz[a]

[a] *Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*
[b] *Department of Environmental Health, Exposure Epidemiology and Risk Program, Harvard School of Public Health, Landmark Center 4th Floor West, 401 Park Drive, Boston, MA 02215, USA*
[c] *Institute for the Environment, University of North Carolina, 137 E Franklin Street, Suite 645, Chapel Hill, NC 27599, USA*
[d] *Department of Civil Engineering, Boise State University, 1910 University Drive, Boise, ID 83725, USA*
[e] *Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK*

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ABSTRACT

Aircraft emissions degrade air quality and cause adverse health effects. Here we quantify the impact of aircraft landing and takeoff emissions on air quality and public health across the contiguous United States. While the approach of using a detailed chemistry-transport model is feasible for specific policy assessments, computational requirements preclude the assessment of a wide range of policy options, quantification of uncertainty, sensitivity studies, or a timely response to policy questions. We therefore develop two surrogate modeling approaches to enable rapid assessment of the impact of aviation emissions scenarios on public health. First, we adapt an existing linearized source–receptor matrix. Second, we perform 25 Community Multiscale Air Quality (CMAQ) simulations to populate the emissions scenario space using a design of experiments approach, from which a response surface model is developed and validated. Using a 2005 aircraft emissions inventory and the response surface model developed from CMAQ model simulations, coupled with census data and fine particulate matter ($PM_{2.5}$) concentration–response functions, we estimate that 210 deaths per year are attributable to aircraft emissions (90% confidence interval: 130–340), with total monetized value across mortality and morbidity of $1.4 billion per year in year 2000 U.S. dollars (90% confidence interval: $550 million–$2.8 billion). Finally, we demonstrate the application of the CMAQ-derived surrogate model in a policy context by assessing the health impacts of (i) a possible low sulfur fuel standard, and (ii) a NO_x stringency regulatory intervention. Our findings demonstrate the viability of surrogate modeling approaches for health impact assessments in the aviation sector.

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1. Introduction

Worldwide demand for air travel is forecasted to grow at an average rate of 5% per year over at least the next 20 years (Schäfer and Waitz, this volume). In some countries–including China and India–annual growth may reach 10%. Emissions from airport activities, including aircraft landing and takeoff (LTO) operations, ground support equipment and airport transportation links are receiving increasing attention from a public health perspective. Quantifying health effects attributable to aviation is important for informing the development of environmental mitigation policies for the aviation industry.

The annual average fine particulate matter ($PM_{2.5}$) concentration is the air pollution exposure metric that is most consistently and independently associated with adverse health impacts including premature mortality (USEPA, 1999, 2004a; Watkiss et al., 2005; Ostro, 2004). While exposure to other pollutants (e.g. ozone, nitrogen dioxide) and differing $PM_{2.5}$ compositions is thought to have an effect, current evidence suggests that the effect of long-term $PM_{2.5}$ concentrations on mortality may explain the majority of monetized air pollution-related public health impacts.

As aircraft emit both primary $PM_{2.5}$ and gaseous aerosol precursors, health damages may be distributed over local to regional scales. Previous studies of the impact of airport emissions on ambient air quality have not considered the contribution to health risks nationally (Yu et al., 2004; Carslaw et al., 2006, Schurmann et al., 2007; Unal

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E-mail address: e.brunelle.yeung@gmail.com (E. Brunelle-Yeung).

[1] Now at: Massachusetts Institute of Technology.

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et al., 2005). In the near-airport vicinity, statistical techniques applied to ambient monitoring data have been used to infer the contribution of aircraft activity to pollutant concentrations (Carslaw et al., 2006). On the regional scale–where the contribution of aircraft to pollutant concentrations becomes small compared to other sources–atmospheric chemistry-transport modeling may be employed (e.g. Unal et al., 2005).

In this paper, we apply the Community Multiscale Air Quality (CMAQ) chemistry-transport model (Byun and Ching, 1999; Byun and Schere, 2006) to estimate the impact of aircraft LTO emissions on air quality and public health across the contiguous United States. CMAQ is a comprehensive, multi-scale, one-atmosphere chemistry-transport model that includes treatment of gas-phase chemistry, particulate matter and air toxics. CMAQ–along with comparable chemistry-transport models–is computationally intensive with current computer runtimes of about three days per simulated year, for national applications at 36 km grid resolution. This level of computational cost may preclude the assessment of as many policy options as may be of interest or prevent detailed characterization of uncertainty, which typically requires many model runs with varying input parameters. It is also important to respond to policy questions in a timely, transparent and resource-efficient manner (National Research Council, 2007). These requirements point to the need for a surrogate modeling methodology to rapidly assess the air quality and public health impacts of a given aircraft emissions scenario. Within this context, two surrogate models were developed with the aim of rapidly quantifying the public health impacts of a given aircraft emissions scenario.

First, we applied a previously developed source–receptor approach based on the intake fraction (iF) concept (Levy et al., 2002, 2003; Marshall et al., 2005; Heath et al., 2006; Greco et al., 2007). This well-characterized methodology has the advantage of allowing for spatially varying emissions-to-exposure relationships and of corresponding well with the generally linear concentration–response functions associated with $PM_{2.5}$. However, iF estimates have not been developed for aircraft sources, which are unique in terms of their vertical distribution and chemical speciation, and iF estimates involve the a priori assumption that exposure responses are linear with emissions.

Second, we developed a new response surface model (RSM) based on 25 CMAQ simulations, which relates changes in national aircraft fuel burn, fuel sulfur content, NO_x emissions, and non-volatile primary PM emissions to changes in ambient $PM_{2.5}$ concentrations. This model captures the detailed underlying chemical and transport processes involved in the formation of fine particulate matter with aviation-specific emissions characteristics, but does not allow for airport-specific impacts to be extracted.

Using each of these models, we estimated the $PM_{2.5}$ concentration changes associated with aircraft emissions and linked these outputs with concentration–response functions for morbidity and mortality. We also presented results in economic terms (applying previously derived monetization techniques for health endpoints), which may allow policy-makers to compare across environmental domains (e.g. climate change versus air quality), and provide a quantitative (if uncertain) basis for judging whether the economic cost of a proposed environmental policy intervention is justified by the environmental benefits that it may yield.

2. Methodology

2.1. Emissions inventory

Our analysis was based on aircraft emissions for the year 2005 below an assumed mixing height of 3000 feet (914 m) above ground level.[2] The U.S. EPA considers aircraft emissions below 3000 feet (914 m), comprised of emissions from the LTO cycle, to be the most significant contributors to air quality, as compared to emissions released during operations at higher altitudes (USEPA, 1992). Historically, cruise emissions from aircraft have not been considered important factors in surface air quality, although recent studies (Barrett et al., 2010, 2012) have found that cruise emissions do impact surface air quality.

The emissions inventory used in this study was generated with the Emissions Dispersion Modeling System (EDMS), part of the FAA's Aviation Environmental Design Tool (AEDT) (CSSI, 2007). EDMS was used to calculate particulate soot, sulfate and organic emissions, along with gaseous NO_x, SO_2, and volatile organic compounds (VOCs) produced during the LTO cycle for 310 airports in the contiguous United States. The operations at these airports account for 95% of commercial aviation activity in the U.S. (CSSI, 2007). Particulate matter emissions were calculated using the First Order Approximation (FOA3) (Wayson et al, 2009).

For emissions, we estimated uncertainty based on available data at the time of our analysis, noting that formal assessment and validation studies of AEDT/EDMS are on-going. Although detailed assessment results are available for global emissions (Lee, 2005; Kim et al., 2007), for this study we are interested in inventories below 3000 ft (914 m), which carry more uncertainty due to the large impacts of assumptions such as engine power settings or times-in-mode (e.g. time spent taxiing).

Lee (2005) performed Monte Carlo simulations and estimated the uncertainty in fleet-averaged emissions for an emissions inventory tool known as AEDT/SAGE. Assumptions on uncertainty for AEDT/EDMS were taken to be the same as for AEDT/SAGE. Specifically, it was assumed that uncertainty could be captured by applying mean shifts to the AEDT/EDMS inventories. Mean shifts were expressed as uncertainty coefficients having uniform distributions between 0.92 and 1.12 for fuel burn and SO_2, 0.83 and 1.23 for NO_x, and 0.52 and 2.06 for primary PM. The fuel sulfur content (FSC) was assumed to have a nominal value of 680 ppm (by mass) and an additional uncertainty coefficient following a Weibull distribution was applied to the SO_2 inventory to capture variability in FSC based on Petroleum Quality Information Systems (PQIS) data for U.S. JP8 fuel (DESC, 2002–2007). The AEDT/EDMS emissions with estimated uncertainty ranges are presented in Table 1 of Supplementary information.

2.2. Exposure assessment

We developed two reduced-order models to characterize the relationship between aircraft emissions and ambient $PM_{2.5}$ concentrations–an iF model derived from an existing source–receptor matrix and a new response surface model based on 25 CMAQ simulations. Note that the emitted pollutant is not the same as the exposure measure for secondarily-formed pollutants. For example, ammoniated sulfate and ammoniated nitrate are the exposure measures estimated as a function of SO_2 and NO_x emissions.

3. Intake fraction model

We applied iFs for primary and secondary $PM_{2.5}$ developed by Greco et al. (2007). The iFs were estimated from a source–receptor (S–R) matrix derived from the Climatological Regional Dispersion

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[2] Total aircraft fuel burn in 2012 is comparable to that in 2005, due to two largely offsetting trends, i.e., a roughly 5% higher revenue passenger-km and small annual but continuous fuel burn reductions. Because baseline emissions scale with fuel burn, we expect today's emission to be comparable to those in 2005, i.e., the base year of the analysis.

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