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Development of a response surface model of aviation's air quality impacts in the United States

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HIGHLIGHTS

- A response surface model (RSM) for the air quality impacts of aviation is developed.
- The RSM is applicable for present-day and future aviation emissions scenarios.
- We quantify aviation's U.S. air quality impacts now and in the future.
- Emissions mitigations required as a function of air quality goals are quantified.

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ABSTRACT

The air quality impacts of aviation are becoming increasingly important given their impact on human health and the projected growth of aviation. In the United States, the government has set targets to manage and reduce the environmental impacts of aviation. In an environmental policy assessment context it is often necessary to rapidly evaluate many possible scenarios, and quantification of uncertainty is important. This makes direct application of comprehensive air quality models such as the Community Multiscale Air Quality (CMAQ) modeling system impractical due to computational cost. Here we develop a response surface model (RSM) – a form of rapid surrogate model – of the impact of aviation emissions on air quality in the United States. We develop an RSM design space and populate it with results from 46 CMAQ simulations, and perform cross-validation of the resultant RSM. The RSM models present-day as well as future impacts amid changing population and non-aviation emissions sources. This enables rapid estimates of the (particulate matter) air quality and human health impacts of aviation emissions scenarios. Cross-couplings between precursor gaseous emissions and $PM_{2.5}$ species are found, consistent with competition for atmospheric ammonia. We apply the RSM to quantify the human health benefits of emissions reductions in 2018. Using the RSM we estimate that in 2005, aviation landing and takeoff emissions cause ~195 [90% CI: 80–340] early deaths, while the same emissions cause ~350 [90% CI: 145–610] mortalities in 2018. An emissions tradespace between aviation NO_x and SO_x emissions is constructed. It is found that with fleet-wide desulfurization of jet fuel, a 35% reduction in aviation NO_x emissions would result in maintaining the same level of aviation-attributable early deaths in 2018 relative to 2005 levels, while an 80% reduction in NO_x emissions would half aviation-attributable early deaths.

1. Introduction

The air quality impacts of aviation are becoming increasingly important with U.S. commercial aircraft operations projected to grow by more than 60% by 2040 compared to 2010 (FAA, 2011a). The effective management and reduction of the environmental impacts of aviation is a key objective of the U.S. government (USC, 2005; JPDO, 2010).

The main air quality impact of aviation emissions is premature mortality due to exposure to fine particulate matter ($PM_{2.5}$) (Ratliff et al., 2009). There have been several studies aimed at quantifying the human health impacts of aircraft landing and takeoff (LTO)

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emissions – i.e. the regulated portion of emissions below 3000 ft above field elevation. Ratliff et al. (2009) estimated that 160 (range: 67–270) premature mortalities occur due to U.S. aviation emissions in 2005, while Brunelle-Yeung (2009) estimated 210 deaths (range: 130–340). Using activity data from 99 U.S. airports in 2005, Levy et al. (2012) estimated ~75 early deaths per year are due to aircraft LTO emissions.

Beyond LTO emissions, aircraft cruise emissions have also been found to impact surface air quality and human health (Barrett et al., 2010, 2012), although they are not currently regulated. While LTO emissions are a local-to-regional air quality issue, cruise emissions can be characterized as being an intercontinental air pollution issue (Koo et al., 2013). In this paper only LTO emissions are considered with their regional-scale impacts.

Aviation policies have also been studied with the objective of assessing approaches to mitigate aviation's air quality impacts. It has been estimated that the aviation NO_x emissions stringency measure recently agreed to by the International Civil Aviation Organization (ICAO) Committee on Aviation and Environmental Protection (CAEP) will avert ~10 premature mortalities per year by 2036 (Mahashabde et al., 2011). Desulfurizing aviation jet fuel was found to reduce annual premature mortalities in the U.S. by 120 (range: 46–210, ~15% reduction) when considering global, full-flight implementation (Barrett et al., 2012).

Aviation policy measures are typically assessed for 20–30 years into the future, due to the technological time constant of aviation (Mahashabde et al., 2011). Levy et al. (2012) highlighted the importance of explicitly assessing aviation's future-year air quality impacts when they estimated a six-fold increase in aviation-attributable premature mortalities in 2025, brought about by a combination of aviation activity growth, changes in non-aviation emissions, and population growth and aging. Woody et al. (2011) found a 60% increase in $PM_{2.5}$ concentrations in 2025 relative to 2005 while holding aviation emissions constant. We also note that policy analyses involve the assessment of multiple scenarios – for example six candidate measures were assessed for the recent ICAO/CAEP round by Mahashabde et al. (2011) – along with the quantification of uncertainty. This is done to facilitate the selection among several policy options, analyze tradeoffs with respect to other cost or environmental aspects, and quantitatively understand the uncertainty in costs and benefits of policy options.

Considering the needs of environmental policy analyses (specifically, rapid execution with uncertainty quantification) we develop a response surface model (RSM) of aviation's air quality impacts in the United States. In this context an RSM is a surrogate representation of a more complex air quality model, enabling rapid analysis of multiple aviation scenarios as well as propagation of uncertainties in emissions through to the air quality and health impacts by use of Monte Carlo or other methods.

The concept of the RSM has been employed in several other studies (Digar and Cohan, 2010; Wang et al., 2011; Xing et al., 2010) and by the U.S. EPA (2006) to model $PM_{2.5}$ and ozone from emission source sectors. An early effort to develop an RSM for aviation was made in thesis work by Masek (2008), with a policy cost-benefit framework for this developed by Brunelle-Yeung et al. (2010).

We first describe our hypothesis-driven RSM design approach. The air quality model and response surfaces are then validated, following which the response surfaces themselves are analyzed to quantify the interactions between aviation emission and the resulting ambient aerosol concentrations. Finally, the RSM is applied to quantify the benefits to human health impact of potential aviation emissions reductions in the future.

2. Methodology

2.1. Overall RSM design

The aviation air quality RSM is a mapping of aviation emissions (inputs) to ambient annual mean aviation-attributable $PM_{2.5}$ concentrations (outputs), and is derived statistically based on an ensemble of results from computationally-intensive air quality model simulations. We applied the Community Multiscale Air Quality (CMAQ) model (Byun and Schere, 2006) to generate this ensemble of outputs. Each CMAQ simulation results in pollutant concentrations for a specific aviation emissions sample (or scenario). Taken together, these samples populate the RSM emissions (input) design space. This emissions design space spans the future projected changes and uncertainty bounds of each emissions species and defines the range of applicability of the RSM.

Aviation-attributable $PM_{2.5}$ is computed for each CMAQ simulation in the set, which is then collectively used to generate the functional mapping on a CMAQ grid-cell basis. We select a linear response surface as the functional form of the RSM. This is based on sensitivity tests conducted by Masek (2008) in which an ordinary least-squares (OLS) linear regression produced lower errors in off-design scenarios (i.e. in between the RSM sample points) compared with ordinary and universal kriging interpolation models. Nonlinearities are not captured by the linear model; however, the residual errors from the linear model are ~1% from a similar application (Masek, 2008). Concentrations are population-weighted to assess exposure to pollutants. Health impacts – specifically, premature mortalities – attributable to aviation emissions are calculated through the use of a concentration response function (CRF).

The various sources of uncertainty and variability in the pathway from aircraft emissions to health impacts are quantified in the RSM through a Monte Carlo assessment. As it would be impractical to do a Monte Carlo simulation directly with CMAQ, this is possible given the reduced computational complexity of the RSM (described in Section 3.2). We propagate the uncertainties associated with aircraft emissions, the regression model and the health impact CRF in the RSM. The distributions that are assumed for aviation emissions are specified in Section 2.5, the error bounds for the RSM regression surfaces in Section 3.1 and the range of CRF values in Section 2.3.

The main limitation of the RSM approach is that it is restricted by the design space used – which in this case is appropriate for evaluating the air quality impacts of national-scale policies (such as desulfurizing jet fuel or introducing NO_x emissions reduction measures). This is because our choice of design space assumes uniform relative changes in emissions nationwide, although methods have been developed to approximately account for regionally-varying policies (Masek, 2008).

2.2. Impact in future years

The aviation-attributable $PM_{2.5}$ concentration has been shown to increase by 60% amid a changing background scenario from the year 2005 to the year 2025 (Woody et al., 2011), while holding aviation emissions constant. Woody et al. (2011) explain the increase in ammonium nitrate aerosol, the dominant factor leading to the increased future-year aviation impacts, by increased concentrations of free ammonia as a result of higher ammonia and lower non-aviation NO_x emissions forecast in 2025.

Given that aviation policies are often assessed over 20–30 years, it is necessary to account for changes in future-year aviation impacts due to a changing background scenario. We therefore create two response surfaces for each $PM_{2.5}$ species: one representing the response under current-day conditions, in which the