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Reduced-form modeling of public health impacts of inorganic $PM_{2.5}$ and precursor emissions

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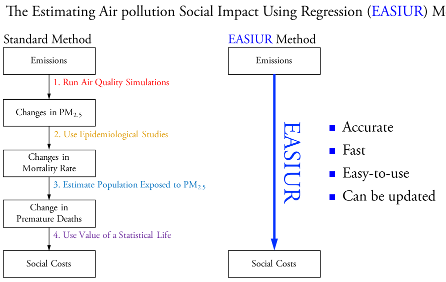
HIGHLIGHTS

- Method brings results from detailed chemical transport models to policy analysis.
- Method estimates marginal social cost and intake fraction accurately and quickly.
- Reduced-form models produce errors comparable to state-of-the-art models' errors.

GRAPHICAL ABSTRACT



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ABSTRACT

It is challenging to estimate the public health costs of fine particulate matter ($PM_{2.5}$) and its precursor emissions accurately and quickly for policy research because of their complex physical and chemical processes occurring over a large downwind area. We developed a method for building statistical regressions that estimate public health cost of emissions accurately like a state-of-the-art chemical transport model (CTM) but without its high computational cost. This method achieves detailed spatial resolution according to the location of the emission source, accounting for differences in the exposed population downwind. Using tagged CTM simulations, our method builds a large dataset of air quality public health costs from marginal emissions throughout the United States. Two methods were developed to describe exposed population, one that assumes a generic downwind plume concentration profile derived from CTM outputs and a simpler method that uses the size of population within certain distances as variables. Using the former method, we parameterized marginal public health cost [$/t] and intake fraction [ppm] as a function of exposed population and key atmospheric variables. We derived models for elemental carbon, sulfur dioxide, nitrogen oxides, and ammonia. Compared to estimates calculated directly using CTM outputs, our models generally show mean fractional errors of only 10%–30% and up to 50% for NO_x in some seasons, which are generally similar to or less than CTM's performance. Our results show that the public health costs of emissions can be efficiently parameterized for policy analyses based on state-of-the-art CTMs.

1. Introduction

Accurate estimation of the impact of air pollutant emissions on society is valuable in several decision making arenas. Human

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activities such as generating electricity, heating and cooling, and transportation emit air pollutants, imposing undesirable burdens on humans and the natural environment. Strongly associated with cardiovascular and cardiopulmonary premature mortality (Pope and Dockery, 2006), fine particulate matter ($PM_{2.5}$) imposes serious public health burdens. In 2010, ambient particulate matter pollution was the 9th leading contributor (3.2 M–3.3 M premature deaths/year) to the global burden of disease (Lelieveld et al., 2015; Lim et al., 2012) and the 8th (103 k premature deaths/year) in the United States (US Burden of Disease Collaborators, 2013). Ambient $PM_{2.5}$ consists partly of primary (directly emitted) species, but mostly of secondary (chemically produced from gaseous precursors) species. Therefore, accurate estimation of air quality impacts must account for atmospheric chemical processing, which depends on meteorological conditions and frequently exhibits nonlinear behaviors. The major precursors for secondary $PM_{2.5}$ include sulfur dioxides (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), and volatile organic compounds (VOCs).

A common way of quantifying the societal impacts of air pollution is based on an impact pathway analysis that converts air pollutant emissions to ambient concentrations, estimates their societal effects (e.g. premature mortality and other health effects), and monetizes these outcomes using estimates of willingness-to-pay to avoid these effects. It is a standard method used by the U.S. EPA in benefit-cost analyses of the Clean Air Act (U.S. EPA, 2011a, 1999) and other regulatory impact analyses. According to analyses based on this method (U.S. EPA, 2011a, 1999; National Research Council, 2010), premature mortality associated with $PM_{2.5}$ accounts for more than 90% of the monetized damages of air quality on public health and the environment. Therefore, policy analyses often focus on the mortality effects of $PM_{2.5}$.

A convenient measure to estimate the social cost of emissions is marginal social cost, which is public health cost caused by “marginal,” or relatively small, amount of emissions, or marginal social benefit in case of marginal emission reductions. For inert primary $PM_{2.5}$ species, marginal benefit and marginal cost would have the same magnitude and public health cost is expected to be proportional to the amount of increased emissions when the characteristics of population exposure and meteorology are held constant. For secondary species with nonlinear behaviors, marginal effects may differ depending on whether emissions increase or decrease or whether baseline emissions of related species change. However, there would be a certain range of marginal emissions where marginal effects stay similar. For policy interventions that result in such marginal changes, their social cost can be easily calculated by multiplying marginal social cost by the change in emissions.

Intake fraction is a similar measure widely used to quantify the public health effects of emissions (Bennett et al., 2002). For atmospheric emissions, intake fraction is defined as the fraction of emissions that are inhaled by an exposed population. Compared to social cost, intake fraction focuses on characterizing the relationship of emissions to population exposure.

Policy research often requires quickly comparing many different policy options and exploring associated uncertainties. Current air quality tools face significant limitations in achieving this goal. Current tools may be divided into three categories. First, chemical transport models (CTMs) such as CAMx (ENVIRON, 2012) and CMAQ (Byun and Schere, 2006) are the most rigorous tools for simulating air quality. CTMs divide the atmosphere into a three-dimensional grid and attempt to simulate all the relevant processes of pollutant transport, chemical reaction, and removal of particles and gases in the atmosphere. Because CTMs are computationally expensive, several CTM add-ons were developed to enhance computational efficiency such as Particulate Source Apportionment Technology (PSAT) (Koo et al., 2009; Kwok et al., 2015; Wagstrom et al., 2008), Direct Decoupled Method (DDM) (Dunker et al., 2002; Koo et al., 2007), and Adjoint (Hakami et al., 2007; Henze et al., 2007). PSAT puts tags on emission sources to track their contributions at multiple receptor locations. DDM allows to find sensitivity of emission sources and parameters to results at multiple receptors. Conversely, Adjoint method calculates sensitivity of changes in receptors to sources and parameters. However, being still computationally demanding, these sensitivity techniques may reduce CTM's computational burden one or two orders of magnitude but not more than that. Because running CTMs with or without such an add-on are computationally expensive, they are often employed for a limited number of scenarios even for important regulatory impact analyses.

Second, tools such as COBRA (U.S. EPA, 2013) and APEEP/AP2 (Muller, 2011; Muller and Mendelsohn, 2009) estimate social costs for all (~3000) U.S. counties using the Climatological Regional Dispersion Model (CRDM) (Latimer, 1996), which a CTM would require roughly 6000 CPU-years to generate according to our back-of-envelop calculation. However, Gaussian dispersion models such as CRDM have fundamental limitations. They assume that meteorological conditions at the source are held constant for all downwind areas, posing potential problems in predicting secondary $PM_{2.5}$ formations. These dispersion-based models have at best simple treatments of inorganic $PM_{2.5}$ formation chemistry and rely on an outdated understanding of organic $PM_{2.5}$ formation from volatile organic compounds, which has substantially revised in recent years (Robinson et al., 2007).

Lastly, there are per-ton social costs estimated by a statistical model built using CTM outputs (Fann et al., 2009; U.S. EPA, 2006) and by directly using CTM simulations (Fann et al., 2012; U.S. EPA, 2014). However, due to their CTM's high computational costs, their estimates are limited to certain urban areas and/or national averages for a selected set of sectoral emissions. Therefore, they do not provide a high spatial resolution according to emissions source, which is frequently useful in policy research. In short, because of current tools' limitations, a large part of policy research community is not able to incorporate the latest atmospheric science into their work.

In this paper, we present a new method called Estimating Air pollution Social Impacts Using Regression (EASIUR). The goal of the EASIUR method is to overcome the limitations noted above by deriving parameterizations that estimate marginal social costs [\$/t] and intake fractions [ppm] from a large dataset of tagged simulations created by a CTM. The parameterizations provide a high spatial resolution similar to the county scale of CRDM and their outcomes produced with negligible computational costs are very similar to CTM-based estimates. As a proof of concept, we present the method and evaluation of the EASIUR model for one primary $PM_{2.5}$ species (elemental carbon) and three secondary inorganic $PM_{2.5}$ precursor species (sulfur dioxide, nitrogen oxides, and ammonia) for four seasons and for three emission heights: ground-level area emissions and two stack-height (150 m and 300 m) point sources. This paper focuses mainly on marginal social cost and most equivalent parts associated with intake fraction are included in the Supporting Information (SI). Challenges that are addressed in this study include finding methods to estimate downwind exposed populations, assessing the length of CTM simulations required, and finding methods that account for seasonal and other differences in atmospheric processing. EASIUR model's estimates and associated uncertainties are presented and discussed comprehensively in a separate study (Heo et al., 2016).