



Urban emissions hotspots: Quantifying vehicle congestion and air pollution using mobile phone GPS data[☆]



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ABSTRACT

On-road emissions vary widely on time scales as short as minutes and length scales as short as tens of meters. Detailed data on emissions at these scales are a prerequisite to accurately quantifying ambient pollution concentrations and identifying hotspots of human exposure within urban areas. We construct a highly resolved inventory of hourly fluxes of CO, NO₂, NO_x, PM_{2.5} and CO₂ from road vehicles on 280,000 road segments in eastern Massachusetts for the year 2012. Our inventory integrates a large database of hourly vehicle speeds derived from mobile phone and vehicle GPS data with multiple regional datasets of vehicle flows, fleet characteristics, and local meteorology. We quantify the ‘excess’ emissions from traffic congestion, finding modest congestion enhancement (3–6%) at regional scales, but hundreds of local hotspots with highly elevated annual emissions (up to 75% for individual roadways in key corridors). Congestion-driven reductions in vehicle fuel economy necessitated ‘excess’ consumption of 113 million gallons of motor fuel, worth ~ \$415M, but this accounted for only 3.5% of the total fuel consumed in Massachusetts, as over 80% of vehicle travel occurs in uncongested conditions. Across our study domain, emissions are highly spatially concentrated, with 70% of pollution originating from only 10% of the roads. The 2011 EPA National Emissions Inventory (NEI) understates our aggregate emissions of NO_x, PM_{2.5}, and CO₂ by 46%, 38%, and 18%, respectively. However, CO emissions agree within 5% for the two inventories, suggesting that the large biases in NO_x and PM_{2.5} emissions arise from differences in estimates of diesel vehicle activity. By providing fine-scale information on local emission hotspots and regional emissions patterns, our inventory framework supports targeted traffic interventions, transparent benchmarking, and improvements in overall urban air quality.

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1. Introduction

Poor air quality is a major global problem, with outdoor air pollution causing more than 3.3 million annual premature deaths and many more associated cases of illness (Lelieveld et al., 2015). Mobile sources are responsible for a large fraction of air pollutant emissions in the United States. In 2012, more than 75% of carbon monoxide (CO), and 60% of nitrogen oxides (NO_x) were emitted from on- and off-road vehicles (EPA, 2011a), while mobile sources in large urban areas accounted for as much as 90% of local CO emissions (EPA, 2011b).

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Variability in vehicle activity, local meteorology, and urban structure make human exposure to air pollution highly heterogeneous in space and time. More than 45 million people, 14% of the U.S. population, live within 300 feet of a major road, where ambient pollution concentrations from mobile sources are highest and the negative health impacts of exposure to fine particulates (PM_{2.5}), CO, and NO_x are most severe (EPA, 2014a). Spatial gradients of concentration and exposure differ by pollutant. For example, concentrations of black carbon (BC) and NO₂ decline sharply on scales of tens to hundreds of meters (Zhou and Levy, 2007; Zhu et al., 2002), whereas CO and PM_{2.5} concentrations can persist for much greater distances from the source (Zwack et al., 2011a). Moreover, in urban areas large buildings surrounding roadways can form ‘street canyons’ in which vehicular emissions are not rapidly dispersed by atmospheric mixing, causing ambient pollution concentrations to significantly exceed background levels (Zwack et al., 2011b).

By contrast, estimates of the pollutants emitted by vehicles tend to be constructed at highly aggregated scales, both in space (traffic analysis zones (TAZs) or counties), and/or in time (based on annual fuel sales and consumption (Dallmann and Harley, 2010; McDonald et al., 2012), or on estimates of annual vehicle miles travelled combined with average emissions factors (Harley et al., 2001; Schifter et al., 2005; Zheng et al., 2009)). A key shortcoming of such approaches is that per-kilometer vehicle emissions depend on three classes of variables that are often poorly characterized at fine spatial and temporal scales: vehicle demographics (the shares of car versus truck traffic, fuel characteristics, and the vintages of vehicles' fuel economies and pollution controls), traffic congestion (which affects vehicles' drive-cycles and speed/acceleration profiles) and ambient weather conditions (which affects the performance of engine combustion and emission control devices) (Parrish, 2006). Without such detailed data, generalized spatial proxies (e.g., population, road density) are often used to downscale aggregate emissions estimates (Huang et al., 2011; Olivier et al., 2005), ignoring systematic variations in the local distributions of vehicle types and activity. Although recent advances have demonstrated the feasibility of constructing fine-scale vehicle emission flux estimates without extensive downscaling (Gately et al., 2015; McDonald et al., 2014), comprehensive roadway-level emissions inventories based on actual vehicle activity and fleet composition (e.g. Nyhan et al., 2016) remain rare. The principal difficulties are the lack of direct fine-scale observations, and the consequent need to combine potentially incommensurate datasets to approximate the variability of on-road emissions at sub-kilometer, sub-daily scales. Since vehicle emissions factors are so sensitive to changes in the speed and acceleration profiles of each vehicle (i.e. the 'drive-cycle'), capturing this variability at the relevant time scales (minutes to hours) can significantly improve the accuracy of emissions estimates (Nyhan et al., 2016).

In this paper we demonstrate a novel approach to quantifying emission fluxes at length scales of individual roadway segments and time scales of hours. Air quality models run for urban areas often rely on an emissions inventory generated by a travel demand model (TDM) which uses land use and travel survey data to estimate vehicle trips across an urban domain for an average weekday or weekend day (Lazaridis et al., 2008; Snyder et al., 2014). Emissions factors are then assigned to these vehicle trips to produce daily emissions estimates for different pollutants. Typically, the time resolution of these models is several multi-hour periods, such as the morning and evening peak 'rush-hour' congestion periods, while the spatial resolution is traffic analysis zones (TAZs) that vary in size depending on the model used, but often encompass areas roughly similar to U.S. Census Block Groups (10–20 ha in the denser urban core, 5–10 km² in the less dense suburban and rural areas). Here we demonstrate how the traditional TDM approach can be considerably improved upon by leveraging detailed road-specific data on hourly vehicle travel speeds obtained from GPS mobile phone data and hourly traffic volumes from in-road sensors to quantify hourly emissions at the road-scale. Our method combines existing TDM estimates of vehicle trips with additional individual pieces of information over the large urban domain of Eastern Massachusetts, assimilating data at various native spatial and temporal resolutions into a consistent framework. The resulting high-resolution emissions inventory is then used to quantify the relative contributions of hotspots and congestion to urban air quality, and to test the local fidelity of existing coarse-scale inventory products.

2. Methodology

The focus of the present study is the 8640 km² metropolitan

area surrounding Boston, Massachusetts, which encompasses the 101 towns that make up the Boston Metropolitan Planning Organization (MPO) jurisdiction and includes a broad range of road types, settlement patterns and traffic congestion levels (Fig. 1). This area regularly ranks in the top 5 of U.S. urban areas for traffic congestion (Schrank et al., 2012) and the top ten for total vehicle miles traveled per year (FHWA, 2012a). GPS data from in-vehicle mobile phones and on-board navigation systems were used to quantify hourly vehicle speeds on over 67,000 road segments across the domain. We paired vehicle speed data with hourly traffic volume data obtained from in-road sensors to model hourly vehicle activity across the entire regional road network for the year 2012. We calculate emissions for each hour of the year (indexed by h), estimating the flux of five pollutants (CO, NO₂, NO_x, PM_{2.5} and CO₂, indexed by p) emitted by vehicles on each of 280,424 road segments (indexed by l). Pollutant species are emitted by v types of vehicles, traveling at speeds that we discretize into s 5-mph intervals. Each road segment's hourly emission flux (q^*) is the product of the vehicle kilometers traveled (VKT, k^*) on it and an emission factor (f^*) for every combination of v and s , defined as a response surface that is a function of spatially and temporally varying temperature (T) and relative humidity (H):

$$q_{p,l,h}^* = \sum_v \sum_s k_{v,s,l,h}^* \times f_{p,v,s}^*[T_{l,h}, H_{l,h}] \quad (1)$$

We construct a suite of emission factors to encompass the range of vehicle types, travel speeds, and meteorological conditions observed in our study domain from multiple customized runs of the EPA Motor Vehicle Emissions Simulator (MOVES) version 2014a, (EPA, 2014b) with key inputs—county-specific data on fuel composition, vehicle fleet age and composition, and historical meteorology—customized with local data from our domain and target year. Our meteorological variables were obtained from the North American Land Data Assimilation System (NLDAS-2), which reports 0.125° gridded hourly temperature and specific humidity (Xia et al., 2012). Vehicle fleet age distributions and fuel formulation distributions were provided by the Boston MPO. Output from MOVES included combined emissions factors (for running and evaporative emissions) for each pollutant, stratified by vehicle type, road type, fuel type, vehicle speed, ambient air temperature, and relative humidity.

Our fundamental methodological advance is the linking of emission factors to imputed flows of different types of vehicles on a particular road segment in a given hour and traffic speed interval. For this we utilize a high-resolution database of directly measured vehicle speeds obtained from mobile phone and on-board vehicle navigation GPS data provided by the traffic consultancy firm INRIX. The raw data record vehicle speeds on more than 67,000 individual road segments in the study area at 5-min intervals. For computational tractability, these observations were aggregated to produce hourly mean speeds, which were matched to road segments.

The INRIX data over-represent large- and medium-sized roads, which although they account for only 15% of the total road length in kilometers across the domain, represent more than 70% of the total annual VKT. On the road segments for which there were no INRIX records, we imputed speeds based on volume-delay functions (VDF) that relate hourly traffic volumes to average traffic speed using the capacity of the road segment and its typical 'free-flow' speed (Dowling, 1997). VDF parameterizations were taken from the TDM, which uses a modified Bureau of Public Roads (BPR) formula that varies by road functional class and rural-urban context (Eqn. S(1) in the Supporting Information). Because unmodified BPR-based VDFs have been shown to overestimate speeds in congested conditions, the formulas used by the TDM have been calibrated using local traffic counts and directly measured speeds using

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