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Roadway determinants of bicyclist exposure to volatile organic compounds and carbon monoxide

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ABSTRACT

Few studies have quantified relationships between bicyclist exposure to air pollution and roadway and traffic variables. As a result, transportation professionals are unable to easily estimate exposure differences among bicycle routes for network planning, design, and analysis. This paper estimates the effects of roadway and travel characteristics on bicyclist exposure concentrations, controlling for meteorology and background conditions. Concentrations of volatile organic compounds (VOC) and carbon monoxide (CO) are modeled using high-resolution data collected on-road. Results indicate that average daily traffic (ADT) provides a parsimonious way to characterize the impact of roadway characteristics on bicyclists' exposure. VOC and CO exposure increase by approximately 2% per 1000 ADT, robust to different regression model specifications. Exposure on off-street facilities is higher than at a park, but lower than on-street riding – with the exception of a path through an industrial corridor with significantly higher exposure. VOC exposure is 20% higher near intersections. Traffic, roadway, and travel variables have more explanatory power in the VOC models than the CO model. The quantifications in this paper enable calculation of expected exposure differences among travel paths for planning and routing applications. The findings also have policy and design implications to reduce bicyclists' exposure. Separation between bicyclists and motor vehicle traffic is a necessary but not sufficient condition to reduce exposure concentrations; off-street paths are not always low-exposure facilities.

Introduction

While more than 40 studies have measured air pollutant exposure concentrations[2] for bicyclists, studies including intra-modal covariates are still lacking (Bigazzi and Figliozzi, 2014). Several studies have tested the effects of roadway facility types and found lower concentrations of carbon monoxide (CO), nitrogen dioxide (NO_2), ultrafine particles (UFP), and black carbon particulate matter (BC) on more separated bicycle infrastructure (Hatzopoulou et al., 2013b; Kendrick et al., 2011; MacNaughton et al., 2014). A few studies have also tested high-traffic versus low-traffic bicycle routes, finding significant differences in CO, UFP, BC, fine particulate matter ($PM_{2.5}$), and volatile organic compound (VOC) exposure (Cole-Hunter et al.,

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[2] The term "exposure concentration" – referring to the concentration of a pollutant in the breathing zone of bicyclists – is used to distinguish from other exposure measures such as concentration × time or concentration × distance (U.S. Environmental Protection Agency, 2013).

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2012; Jarjour et al., 2013; Weichenthal et al., 2011). High-traffic vs. low-traffic differences are typically larger for the more strongly traffic-related pollutants such as VOC, UFP, CO, and BC (Bigazzi and Figliozzi, 2014).

But bicyclist exposure research frequently fails to find significant associations between more specific traffic or roadway variables and exposure (Adams et al., 2001; Boogaard et al., 2009; Dons et al., 2013; Hatzopoulou et al., 2013b; Kaur and Nieuwenhuijsen, 2009). Hatzopoulou et al. (2013b) reported significant increases in BC exposure of 0.8–1.5% with hourly diesel vehicle (truck and bus) counts. Kaur and Nieuwenhuijsen (2009) reported significant increases in UFP and CO exposure with traffic count (vehicles per hour), but their model included exposure data from travelers using five different modes (including bicyclists). Exposure research for other travel modes has quantified some effects of traffic conditions on travelers' exposure (Bigazzi and Figliozzi, 2012; Fruin et al., 2008), but the transferability to bicyclists is unclear – especially for studies that focus on high-volume arterials and freeways.

Due to poorly quantified traffic-exposure relationships, transportation professionals are unable to easily estimate exposure differences among bicycle routes in the context of network planning, design, and analysis. The goal of this paper is to provide new information to enable bicycle network analysis with consideration of exposure risks. Average daily traffic (ADT) is a commonly used and widely available descriptor of roadways. In this paper, the impact of ADT on bicyclist exposure to VOC and CO is quantified. VOC and CO were selected as traffic-related pollutants with known negative health effects and elevated exposure concentrations for bicyclists on high-traffic routes (Bigazzi and Figliozzi, 2014). In addition, this paper is part of a broader study using breath analysis to investigate absorbed doses of VOCs by bicyclists. The study of $PM_{2.5}$, UFP, BC, and other pollutants is also relevant to health impacts, but outside of the scope of this paper. Models of exposure are estimated from measured on-road data using roadway and traffic variables while controlling for weather and background concentrations. Due to the goal of providing information for route analysis, regression models are developed utilizing ADT and facility-oriented variables.

Data collection

On-road concentration measurements were made in Portland, Oregon, on nine days in the spring and summer of 2013. All on-road data collection was performed in and around the morning peak travel period (7–10 h). A variety of transportation facilities were selected for prescribed sampling routes, including off-street paths and roadways ranging from local streets to major arterials. On-street facilities convey bicycle and motor vehicle traffic in shared lanes or with dedicated on-street bicycle lanes (without physical separation beyond lane markings). 20 h of complete location and air quality data were collected for BTEX and 24 h for CO.

A stationary pre-ride period of 30 min at a low-concentration starting location (Mt Tabor City Park, a 0.8 km^2 park outside of the urban core) was used to measure reference background concentrations for each data collection. This method was used because the fixed-site air quality monitoring station in the study area (Station SEL 10139, operated Oregon Department of Environmental Quality) does not consistently collect VOC data and entire days of CO data were missing during the data collection period. In the modeling described below, concentration data from the pre-ride period were not included in model estimation. Averaged over the year, background CO at the station fell 10% over the 3-h period 7–10 h and concentrations at 7 and 10 h were highly correlated. The reference concentration on each day was thus considered adequate to control for background concentrations during sampling. Wind and temperature were used as additional controls for varying meteorological conditions.

Air quality monitoring

Air quality monitoring instruments were mounted to the bicycles used in data collection. The air quality instruments were selected for precision and portability. Concentrations of total volatile organic compounds (TVOC) were measured using a PhoCheck Tiger (IonScience, Cambridge, UK). The Tiger uses a photoionization detector (PID) with a 10.6 eV lamp, which detects compounds with an ionization potential below 10.6 eV. Individual compounds are not distinguished, and the reported concentrations are in isobutylene-equivalent units. The Tiger measures TVOC at 1 Hz with a range of 1 ppb to 20,000 ppm, resolution of 1 ppb, and accuracy of ±5% (gas-dependent). The Tiger is lightweight (0.72 kg) and portable, capable of operating on battery power for over 4 h. The Tiger is a new model of portable PID within the IonScience PhoCheck line, and so has not yet been used in published studies, to the authors' knowledge. Earlier models of the PhoCheck were used for air quality studies in motor-vehicle environments (Atabi et al., 2013; Chien, 2007; Li et al., 2006). All data were collected within 12 months and 100 operating hours of calibration, in accordance with manufacturer instructions. The instrument was zeroed with a carbon filter at the beginning and end of each collection and the raw readings were adjusted to a zero reference based on the carbon filter readings. The first 15 min after the instrument was turned on were removed for analysis (the warm-up period suggested by the manufacturer).

Carbon monoxide (CO) concentrations were measured using a T15n (Langan Products, San Francisco, California). The T15n uses an electrochemical sensor to measure CO concentrations at 1 Hz with a range of 0–200 ppm and a resolution of 0.05 ppm. The T15n is commonly used for on-road CO measurements (Bigazzi and Figliozzi, 2014; Kaur et al., 2007). All data were collected within 24 months of calibration, in accordance with manufacturer instructions. CO concentrations were adjusted for on-road measured temperature and humidity according to the manufacturer's documentation.