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Impact of bicycle route type on exposure to traffic-related air pollution

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HIGHLIGHTS

- We monitored traffic-related air pollutants along different bike routes in Boston.
- We modeled the impact of route type on BC and NO_2 levels.
- Bike paths were found to have lower levels of BC and NO_2 than bike lanes.
- Vegetation and proximity to intersections influence pollution levels.

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ABSTRACT

Cyclists are exposed to traffic-related air pollution (TRAP) during their commutes due to their proximity to vehicular traffic. Two of the main components of TRAP are black carbon (BC) and nitrogen dioxide (NO_2), which have both been causally associated with increased mortality. To assess the impact of cyclists' exposure to TRAP, a battery-powered mobile monitoring station was designed to sample air pollutants along five bike routes in Boston, Massachusetts. The bike routes were categorized into three types: bike paths, which are separated from vehicle traffic; bike lanes, which are adjacent to traffic; and designated bike lanes, which are shared traffic lanes for buses and cyclists. Bike lanes were found to have significantly higher concentrations of BC and NO_2 than bike paths in both adjusted and unadjusted generalized linear models. Higher concentrations were observed in designated bike lanes than bike paths; however, this association was only significant for NO_2. After adjusting for traffic density, background concentration, and proximity to intersections, bike lanes were found to have concentrations of BC and NO_2 that were approximately 33% higher than bike paths. Distance from the road, vegetation barriers, and reduced intersection density appear to influence these variations. These findings suggest that cyclists can reduce their exposure to TRAP during their commute by using bike paths preferentially over bike lanes regardless of the potential increase of traffic near these routes.

1. Introduction

Cycling has been increasingly promoted as a mode of transportation in cities in the U.S. to reduce the emission of hazardous particulate and gaseous pollutants, decrease traffic congestion, and improve physical activity. In 1991, Congress passed the Intermodal Surface Transportation Efficiency Act (ISTEA) that recognized the increasingly important role of bicycling and walking in creating a balanced, intermodal transportation system. Since then, the Federal government has funded projects to improve the bicycling infrastructure in cities and towns (FHA, 2012). From 2007 to 2011, Boston, Massachusetts, has installed more than 500 bike racks and 50 miles of bike lanes; by 2011, cyclists represented 2.1% of the commuters in Boston, more than three-times the national average (City of Boston, 2010).

In response to an increase in cyclists in urban areas, bicycle safety has received more attention in recent years, and efforts are underway to improve conditions for cyclists (Reynolds et al., 2009). These efforts have not, however, been focused on mitigating air pollution exposure to the cyclist. Accurate methods to assess cyclists' exposure to traffic-related air pollutants (TRAPs) are warranted since cyclists share the roads with cars, buses, and trucks, all of which contribute to TRAP.

TRAP has been associated with several adverse health outcomes including increased asthma, cardiovascular risks, lung cancer risks, fatal myocardial infarction, and increased mortality (Han and Naeher, 2005). Two key components of TRAP are nitrogen dioxide (NO_2) and elemental black carbon (BC). They represent the complex mixture of TRAP and have been causally associated with mortality (Hoek et al., 2013). BC has been shown to increase the risk of adverse cardiovascular events. The effect of BC on mortality is more robust than $PM_{2.5}$ and therefore serves as a better indicator of particle pollution (Janssen et al., 2011). Exposure to outdoor NO_2 is associated with significant respiratory health effects, particularly to asthmatics. Children exposed to a

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5.7 ppb increase in NO_2 have 1.83 (95% CI = 1.04–3.22) times the odds of doctor-diagnosed asthma (Gauderman et al., 2005).

Several studies have investigated cyclists' exposure to TRAP, mainly via comparisons with vehicle commuters and pedestrians. Cyclists are generally at risk for higher exposures to TRAP after accounting for increased minute ventilation rates during their commutes. In addition, cyclists are exposed to higher peak concentrations since in-vehicle concentrations are buffered by limited air exchange (Zuurbier et al., 2010). The increased exposure to TRAP suggests that bicycle commuters are at greater risk of cardiovascular and respiratory damage. Strak et al. (2011) monitored PM_{10}, soot, and particle number along low and high traffic routes and measured lung function, exhaled nitrogen oxide, and respiratory symptoms in 12 participants before, directly after, and 6 h after each bike trip. Bikers on high traffic routes did not have any more acute damage to respiratory function than bikers on low traffic routes. However, Weichenthal et al. (2011) observed an inverse relationship between TRAP exposure and heart rate variability. They measured breathing zone levels of a wide-variety of traffic related air pollutants during hour long bike commutes and measured heart rate variability for 4 h following the commute. To our knowledge, no studies have looked at the chronic effects from long-term bicycling exposure.

These results, which were obtained in Canada and Europe, cannot be generalized to the U.S. because of the differences in fuels, vehicle fleet mix, meteorology, urban typology, and road infrastructure between the U.S. and Europe. Of those studies conducted in the U.S., many have relied on gasoline or diesel-powered vehicles to haul their monitoring equipment. TRAP is episodic and highly variable in urban environments. Large, energy-intensive equipment is required to achieve the quick response time and fine temporal resolution necessary to capture rapidly changing TRAP levels. Use of vehicles that generate the pollutants being measured requires an assessment of the monitoring vehicles' contribution to the levels being measured. Vehicles are also limited in their capacity to access all routes or lanes accessible to cyclists, potentially limiting the accuracy of the cyclist's exposure assessment.

Some bike routes allow cyclists to reduce their exposure to TRAP compared to vehicle commuters by travelling adjacent to traffic and bypassing heavily polluted intersections (Gee and Raper, 1999). Specific characteristics of urban environments (e.g. proximity to major roads, street canyons, tree-lined streets and traffic patterns) all play a role in determining the level of exposure in the cycling microenvironment. Jarjour et al. (2013) and Hertel et al. (2008) both showed that exposure to TRAP can be greatly reduced by choosing low-traffic bike routes. While traffic levels remain difficult to control, urban planners can reduce exposures to TRAP with smart bike route development.

In this study, exposure to NO_2 and BC during morning and evening commutes is determined for three bike route types in Boston, Massachusetts: bike path, which is a separated lane from vehicle traffic; bike lane, which is adjacent to vehicle traffic; and designated bike lane, which is a shared traffic lane for bicycles and buses. A mobile monitoring platform was designed to measure NO_2, BC, carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), particle mass concentration less than 2.5 μm in diameter ($PM_{2.5}$), $PM_{2.5}$ elemental composition, particle number count, particle extinction coefficient, temperature, relative humidity, atmospheric pressure, wind speed, wind direction, video of adjacent traffic, and GPS location along these routes. Focusing on NO_2 and BC, we hypothesize that bike lanes and designated bike lanes have higher NO_2 and BC concentrations than bike paths.

2. Methods

Air pollution measurements were collected during morning (7:00 am to 10:00 am) and evening (3:00 pm to 6:00 pm) commutes along pre-designated bike routes in Boston. The bike routes were selected to represent travel over a variety of bike route types during variable traffic and atmospheric conditions. A total of five routes were selected and each route was monitored four times (Table 1). A total of 263 km (163 miles) were monitored. Cycling was continuous with breaks every hour or when riding by a fixed-site monitoring station in order to obtain a wind speed and direction reading. Wind speed and direction measurement locations were consistent within each route.

The monitoring equipment was towed behind a bicycle on a mobile monitoring platform. Four 18 A h batteries provided AC power to all the instruments for 5 h, eliminating the concern of self-sampling emissions produced by a fuel-powered platform. All monitoring instruments were housed in a SKB rotoshock rack transport case to reduce vibrations that may interfere with the instruments. Despite this precaution, measurements of $PM_{2.5}$ and particle counts were interrupted by vibrations, resulting in incomplete datasets.

BC was measured with an AethLabs (San Francisco, CA) microAeth® Model AE51 black carbon aerosol monitor. The attenuation (ATN), a measure of the light absorbance of the particles, is measured relative to an adjacent 'Reference' portion of the filter once per sampling period. The gradual accumulation of optically-absorbing particles leads to a gradual increase in ATN from one period to the next. The concentration is calculated using the flow rate and the change in ATN. The BC concentration, which was recorded every second, was averaged over time intervals where ATN increased by 0.02, according to the Optimized Noise-Reduction Averaging method (Hagler et al., 2011). If the ATN increased by 0.04 or greater over the course of 1 min, both recorded data points were deemed imprecise and removed. As an additional measure to reduce noise, the top and bottom percentiles were removed from the dataset. The resulting sensitivity is 1 ng/m^3 within a range of 0–1000 ng/m^3.

NO_2 measurements were obtained with Aerodyne Research's (Billerica, MA) CAPS NO_2 Monitor, which uses a direct absorption measurement to eliminate sensitivity to other nitro-containing species (Kebabian et al., 2005). A reading was recorded every second but averaged to the nearest minute for statistical analyses. Using the fast response logging interval, the sensitivity is less than 1.5 ppb. Since different quality control measures were applied for BC and NO_2, the datasets have different points excluded from analysis. As a result, traffic and vegetation density are slightly different in each dataset due to the exclusion criteria (Table 2).

Temperature, relative humidity, atmospheric pressure, CO, and CO_2 were measured using TSI's model 7565 Q-trak indoor air quality monitor. A reading was recorded every 30 s. RainWise's (Bar Harbor, ME) WindLog Wind Data Logging Device was used to record wind speed and direction when the mobile monitoring platform was stopped. The operator of the mobile platform would point the WindLog in the northerly direction and record the stop and restart time on his log.

The position of the mobile monitoring platform was recorded every second or every 5 s using a Q STARZ (Taipei, ROC) model BT-1000XT GPS travel recorder. Data collected within 120 m of the Landmark Center (42.344819 N, 71.102326 W), where each of the routes started and ended, was removed because the satellite signal was unreliable (Fig. 1). When a 5-second sampling time was used, the location of pollution data recorded within that 5-second window was linearly interpolated. Routes were created by matching one-minute GPS readings

Table 1
Length in kilometers and sampling size of sampling routes and bike route types.

Route type	Route						Sample size	
	1	2	3	4	5	Total	BC[a]	NO_2[b]
Bike path	1.4	5.7	5.7	4.4	0	17.3	257	381
Bike lane	10.2	10.7	9.4	7.7	10.6	48.6	818	1478
Designated bike lane	0	0	0	2.6	0	2.6	19	40
Total	11.6	16.4	15.2	14.6	10.6	68.4	1094	1899

[a] Averaged by time periods with a 0.02 change in attenuation.
[b] Averaged to the nearest minute.