Healthy Commute? Traffic Conditions, Ambient Air Pollution, & Cyclist Exposure

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ABSTRACT

Bicycle commuting is one way to improve public health by increasing activity level while also mitigating climate change through the reduction of climate active vehicle emissions. However, more extensive evaluation of elevated exposures to air pollution and potential health risks associated with these exposures is necessary. In this study, eight adults cycled on high-traffic and low-traffic routes carrying pollutant monitoring devices. We measured lung function using spirometry and heart-rate variance pre-ride, post-ride, and four hours afterward to evaluate health effects. Average concentrations on the high-traffic route were higher than those on the low traffic route for ultrafine particulate matter (in particles per cubic meter: 19172 high, 10884 low), carbon monoxide (in milligrams per cubic meter: 1.16 high, 0.80 low), and black carbon (in micrograms per cubic meter: 2.53 high, 1.54 low). Elevated ambient air pollutant concentrations did not correlate with detrimental changes in lung function parameters, which were insignificant. Our results suggest that selecting low-traffic routes can reduce cyclists' exposure to vehicle-related air pollutants.

KEYWORDS

bike commuting, particulate matter, black carbon, carbon monoxide, lung function

INTRODUCTION

Obesity, defined as a body mass index above 30.0, is a growing epidemic in the United States. From 1995-2009, national median obesity prevalence increased from 15.9% to 26.9% of the adult population (BRFSS, 2009). The rise in obesity has been partially attributed to built environments that encourage increased consumption of unhealthy foods and discourage physical activity (Center for Disease Control, 2009). To combat the obesity epidemic, these environments need to be modified. There are significant correlations between land-use mix (distribution of land between residential, commercial, office, and institutional uses), street connectivity (how effectively streets connect a starting point and destination) and behavioral variables, such as time spent driving, that contribute to inactive lifestyles and weight gain (Frank, Andresen, & Schmid, 2004). One study that evaluated the relationship between built environment, transportation habits, and BMI found that one additional hour of automobile travel per day was associated with a 6% increase in the likelihood of obesity (Frank et al., 2004). Basic changes in neighborhood and street layout can encourage active transportation and have a significant impact on the exercise level of residents.

The same built environment changes that could improve public health and physical fitness by increasing active transportation could also help to mitigate climate change by decreasing vehicle miles traveled and thus fuel consumption (de Nazelle & Nieuwenhuijsen, 2010). At year 2000 constant emission levels, on-road transportation will be the largest positive contributor to radiative forcing (0.199 W/m^2) in 2020, and second largest positive contributor in 2100, making it a key target for reduction of climate-active pollutants (Unger et al., 2010). The California Air Resources Board (CARB) Emissions Forecast predicts a statewide total of 506.8 million tonnes of CO_2 equivalent in 2020 (from 474.64 million in 2008), with transportation sources making the biggest contribution. Within the category of transportation, passenger vehicles are forecast to emit 127 million tones of CO_2 equivalent, more than Electric Power (110.4 million tones CO_2 equivalent) or Industrial (91.5 million tones CO_2 equivalent), the most significant sources after transportation (California Environmental Protection Agency, 2010a).

A shift from vehicle commuting to active transportation would have immediate and long-term climate benefits, as vehicle emissions contain both short-lived (persist in the atmosphere on a scale of days to weeks) and long-lived (remain in the atmosphere for decades to centuries) species of greenhouse gases (Unger et al., 2010). Bicycle commuting also provides a higher level of physical activity and a faster commute than simply walking and is significantly negatively correlated with overweight and obesity (Lindström, 2008). In the United States, however, bicycling is a remarkably underutilized method of transportation; even though 40% of car trips are shorter than two miles, cycling is utilized for less than 1% of commutes (Moudon et al., 2005).

The climate and human health related benefits of bicycle commuting should be weighed against the associated risks. Risk of physical injury is one downside to bicycle commuting, but a less visible hazard is exposure to vehicle exhaust pollutants. Vehicle traffic is associated with the production of multiple air pollutants and related health effects. For instance, controlling for meteorological and seasonal fluctuations, traffic intensity remains the primary indicator of fine particulate matter with diameter less than 2.5 micrometers ($PM_{2.5}$) concentration (Giugliano et al., 2005). To demonstrate the effects of particulate matter pollution, in a study of air quality and childhood asthma during the 1996 Olympic Games in Atlanta, significantly decreased traffic flow was correlated with a 16% decrease in particulate matter with diameter less than 10 micrometers (PM_{10}) concentration, and significant decreases in ozone, carbon monoxide and sulfur dioxide. There was a concurrent 11-44% decrease in pediatric asthma health care utilization (outcome measured in hospitalizations, emergency room and urgent care visits for asthma) as compared to the pre- and post-Olympics traffic intervention baseline measurements (Friedman, Powell, Hutwanger, Graham, & Teague, 2001).

Evaluating the association between traffic and pollutant-related health problems is important for protecting the health of active commuters. This information can also be used to inform city-planning decisions that promote active commuting over vehicle use. A London study found a significant correlation between proximity to higher traffic levels while walking, elevated exposure levels, and respiratory symptoms in an asthmatic subject population (McCreanor et al., 2007). Bicycle commuters are typically closer to moving traffic than walkers, and, due to their level of physical activity, have a relatively high respiratory intake. These factors make cyclists an important sub-population to study.

Preliminary studies that evaluate the relationships between bicycle commuting, vehicle exhaust pollutant exposures, and respiratory health effects have yielded inconclusive results (Strak et al., 2010), demonstrating a need for further research. This study will help to fill this gap by comparing the pollutant exposures and associated lung function for cyclists on high-traffic and low-traffic routes. We hypothesize that cyclists will be exposed to higher ambient concentrations of particulate matter and other vehicle exhaust pollutants on high-traffic routes than cyclists that commute on low-traffic routes and that this elevated exposure will manifest in reduced lung function.

METHODS

Study Participants and Design

Through word-of-mouth, I recruited adults affiliated with the School of Public Health. Potential participants completed a screening survey prior to beginning the study and would have been excluded from participation if they were smokers, had cardiac or respiratory conditions (including asthma), or did not have adequate experience bicycling in the city of Berkeley. For the purpose of this study, I deemed individuals adequately experienced if they biked at least once per week and indicated they were comfortable with the study routes. Participants were asked to refrain from alcohol and caffeine starting the evening before they were scheduled to bike.

Data was collected on weekdays between April 14, 2011 and April 28, 2011. Participants biked two different predetermined study routes on separate days in pairs during morning commute hours (8:00-10:00AM). The two routes were similar in length (5-6 miles) and elevation change (~200 feet), but the high-traffic (Figure 1) followed busy streets with more truck and bus traffic, while the low-traffic (Figure 2) followed residential streets, many designated by the City of Berkeley as “Bicycle Boulevards.” I asked participants to cycle at a normal commuting pace and observe bicycle traffic rules.

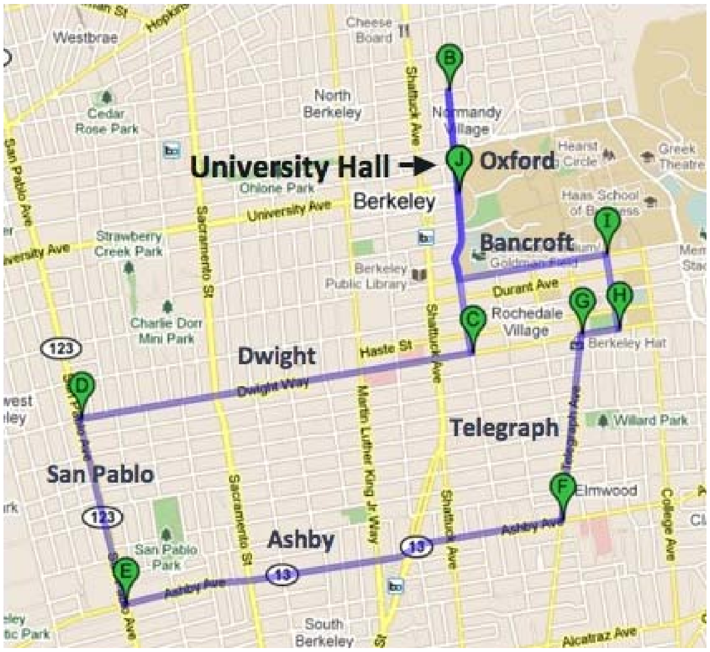

Figure 1. High-Traffic Route. Starting and ending at University Hall, 6.01 mile loop, 220 ft elevation gain.

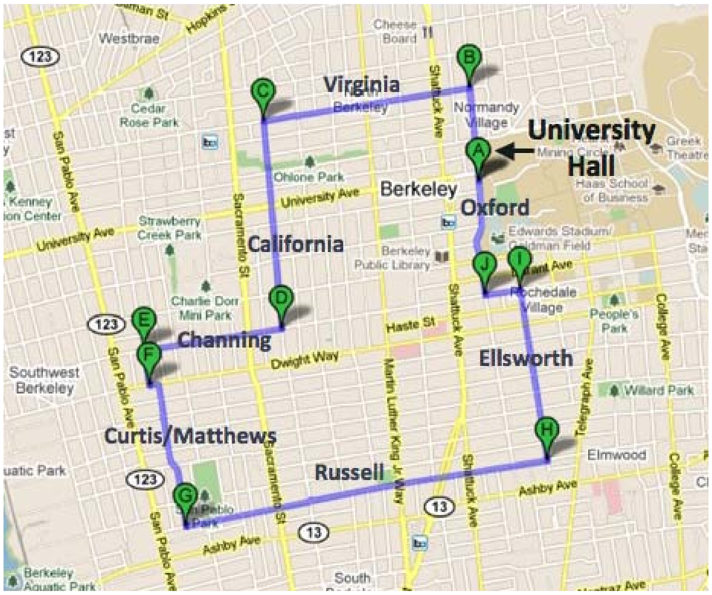

Figure 2. Low-Traffic Route. Starting and ending at University Hall, 5.58 mile loop, 177 ft elevation gain.

Ambient Pollution Concentration Measurements

I used a condensation particle counter (TSI Model 3007) to measure ultrafine particulate matter (0.01 to greater than 1.0 µm diameter) with a logging interval of 10 seconds. CO, CO_2, temperature, and humidity were recorded using a Q-Trak (TSI), also with a logging interval of 10 seconds. I used a DustTrak (TSI) to measure $PM_{2.5}$ with a logging interval of 10 seconds, and a microaethelometer (Magee Scientific) with a logging interval of 1 second to measure black carbon. These devices were placed in a rear basket of one of the subject's bikes. A nitric oxide monitor (2B Technologies, Inc.) with a 10 second logging interval was carried in a rear pannier of the second bike. One subject carried a GPS (Garmin) to track location and speed. I synchronized all monitoring devices to GPS time before each bike ride. After each bike ride, data was downloaded onto a computer using the manufacturers' software.

Health Measurements

I used spirometry to measure lung capacity. Subjects were asked to inhale completely and exhale forcefully into a spirometer (EasyOne Spirometer) at least three times to get an accurate measurement of volume and velocity. I used the parameters forced vital capacity (FVC), the total volume of air the subject was able to expel following complete inhalation, and forced expiratory volume in one second (FEV_1). I measured lung function before biking to establish a baseline, immediately afterward, and four hours later.

To measure heart rate and variability, I used a 5-lead EKG (Forest Medical Holter monitor). Like the lung function measurements, five minutes of resting heart rate data were recorded before biking, immediately afterward, and four hours later. Subjects wore the Holter monitor until after the last resting heart rate recording.

RESULTS

Study Population & Logistics

The study population consisted of eight adults. There were five males and three females, with an average age of 31. None of the subjects identified any pre-existing cardiac or respiratory conditions. Between April 14, 2011 and April 28, 2011, the low-traffic route was completed three times, and the high-traffic route was completed four times. Starting times ranged from 8:43AM to 9:42AM, and bike rides took place on clear days (average temperature range 51-55°F).

Ambient Pollutant Concentration Measurements

The data collection times ranged from 40-43 minutes for the high-traffic route and 33-37 minutes for the low-traffic route. Average cycling speed ranged from 8.9-10.5mph. Due to various technical problems, $PM_{2.5}$ and nitric oxide data will not be discussed. Three runs have been omitted due to a malfunctioning CPC, a flat tire, and a navigational error. Two runs of the high-traffic route (April 19 & April 27, 2011) as well as two runs of the low-traffic route (April 26 & April 28, 2011) had complete ultrafine particulate matter, black carbon, and carbon monoxide data (with the exception of 4/28, which is missing the last ten minutes of CO data); these are the data sets I used for my analysis.

Black carbon data was recorded at a one-second interval, so the data was averaged over 30 seconds, and every tenth point was selected to line up with the ultrafine particulate matter and carbon monoxide data recorded at ten-second intervals. Negative values were assumed to be noise and were removed before averaging. Average carbon monoxide (Table 1), black carbon concentrations (Table 2), and ultrafine particulate matter (Table 3) were all higher on the high-traffic route than on the low-traffic route.

Table 1. Ambient Carbon Monoxide Concentrations. Measurements given in mg/m^3.

	Average ± SD	Minimum	Maximum
High Traffic 4/19/11	1.19 ± 0.85	0.3435	4.9235
High Traffic 4/27/11	1.05 ± 0.61	0.3435	4.122
High Traffic Combined	1.16 ± 0.75	0.3435	4.9235
Low Traffic 4/26/11	0.76 ± 0.45	0.229	3.206
Low Traffic 4/28/11	0.88 ± 0.47	0.229	2.1755
Low Traffic Combined	0.80 ± 0.46	0.229	3.206

Table 2. Ambient Black Carbon Concentrations. Measurements given in µg/m^3.

	Average ± SD	Minimum	Maximum
High Traffic 4/19/11	2.0270 ± 2.2672	0.06867	16.4055
High Traffic 4/27/11	3.3226 ± 6.1961	0.03712	35.6866
High Traffic Combined	2.5274 ± 4.2795	0.03712	35.6866
Low Traffic 4/26/11	1.7431 ± 1.3858	0.06793	6.1506
Low Traffic 4/28/11	1.4219 ± 1.1089	0.00553	6.6660
Low Traffic Combined	1.5399 ± 1.2262	0.00553	6.6660

Table 3. Ambient Ultrafine Particulate Matter Count. Measurements given in number of particles/cm^3.

	Average ± SD	Minimum	Maximum
High Traffic 4/19/11	20,609 ± 28,085	3,646	288,561
High Traffic 4/27/11	17,818 ± 25,983	3,461	261,917
High Traffic Combined	19,172 ± 27,032	3,461	288,561
Low Traffic 4/26/11	7,355 ± 8,490	2,771	78,903
Low Traffic 4/28/11	13,988 ± 12,746	5,269	112,204
Low Traffic Combined	10,884 ± 11,441	2,771	112,204

The ultrafine particulate counts over the course of each bike ride displayed clear peaks, often occurring at intersections, particularly those with busier streets. Elevated concentrations were consistently recorded on Oxford Street at the beginning of both the high-traffic and low-traffic rides. Particle counts over time for each ride are plotted in Figure 3a-d, with the black diamonds marking peaks. Carbon monoxide concentrations over the course of the bike ride oscillated more frequently, and it was difficult to distinguish clear peaks, although elevated concentrations were also seen on Oxford Street. Carbon monoxide concentrations over time for each ride are plotted in the appendix.

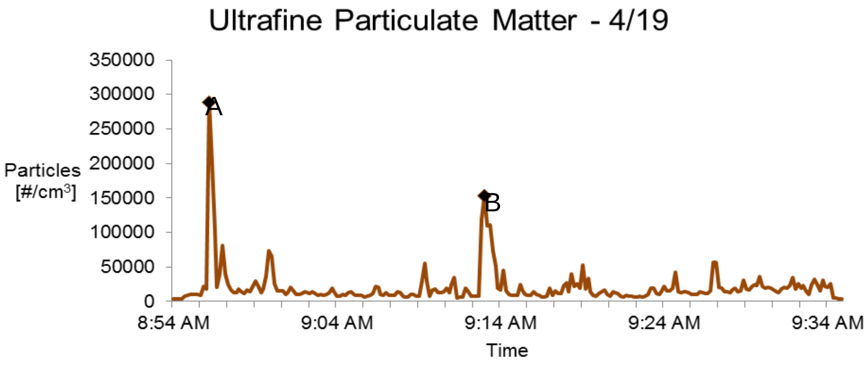

Figure 3a. Ultrafine particulate matter 4/19 (high-traffic route). Peaks at Oxford Street & Berkeley way (A) and San Pablo & Russell (B).

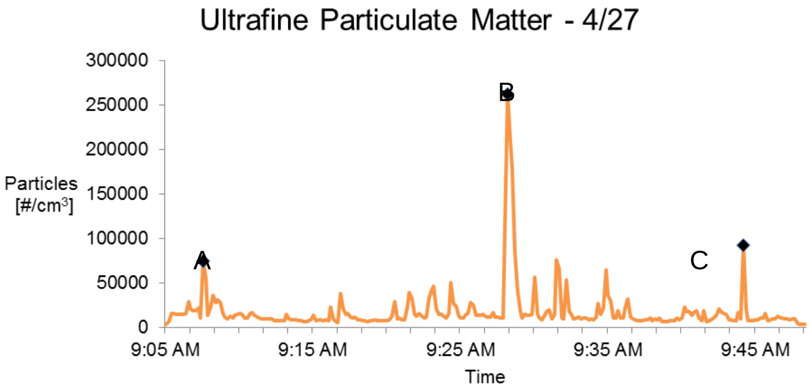

Figure 3b. Ultrafine particulate matter 4/27 (high-traffic route). Peaks at Oxford Street & Hearst Avenue (A) Ashby Avenue near California Street (B), and Bancroft near Telegraph (C).

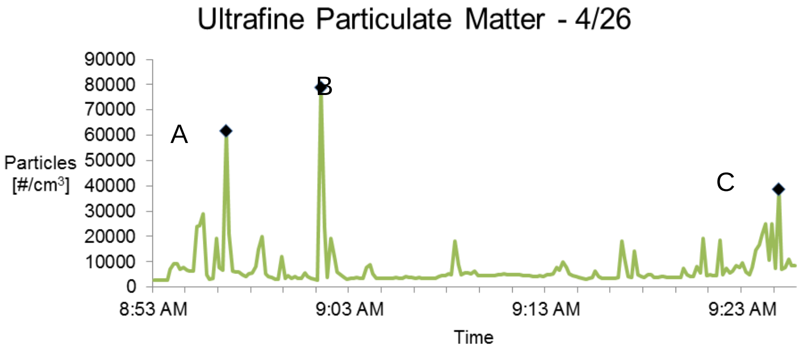

Figure 3c. Ultrafine particulate matter 4/26 (low-traffic route). Peaks at Oxford & Virginia (A), Virginia & California (B), Oxford & University (C).

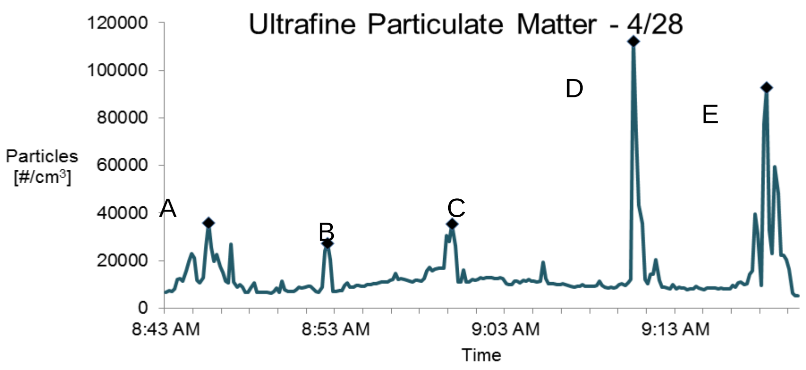

Figure 3d. Ultrafine particulate matter 4/28 (low-traffic route). Peaks at Oxford Street (A), Califronia & University (B), Matthews near Parker (C), Russell & Fulton (D), and Oxford & Addison (E).

For each pollutant, I compared the measurement frequency distributions within the high and low traffic days and between the combined high-traffic and low-traffic measurements. All histograms had a relatively normal distribution with a positive skew. The distributions of carbon monoxide concentrations were similar within low and high traffic days (Figure 4a), but the distribution of the combined low-traffic data is centered at a lower value than that of the combined high-traffic data (Figure 4b). The distributions of black carbon concentrations (Figure 5a and 5b) and ultrafine particulate matter counts (Figure 6a and 6b) also showed overlap within low and high traffic days. Low-traffic concentrations were distributed around lower values than high-traffic concentrations.

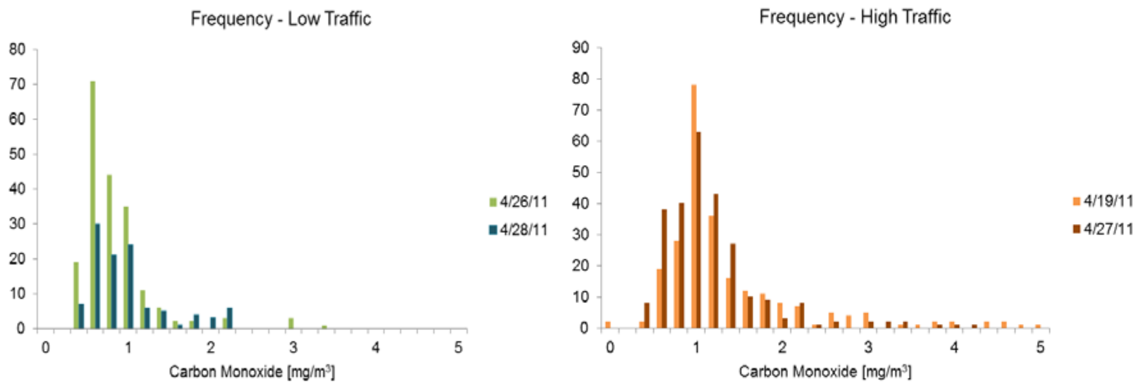

Figure 4a. Carbon monoxide concentration distributions. Comparing frequency of concentrations between two low-traffic rides (left) and two high-traffic rides (right).

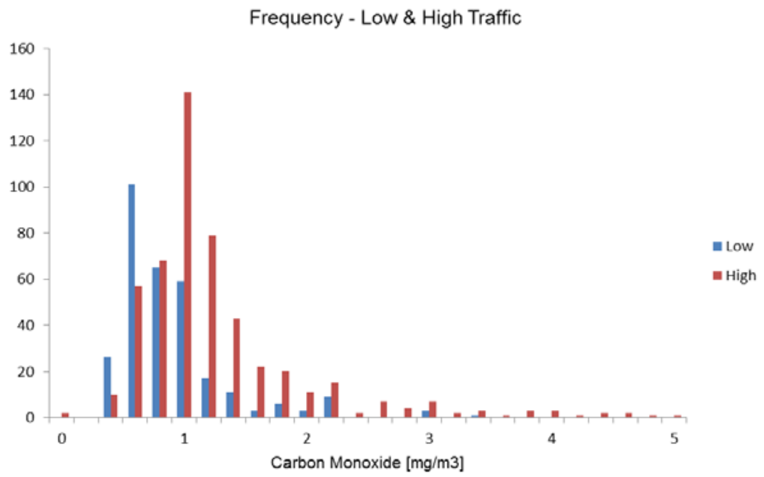

Figure 4b. Carbon monoxide concentration distribution. Comparing frequency of concentrations between combined low-traffic data (average 0.8 mg/m^3) and combined high-traffic data (average 1.16 mg/m^3).

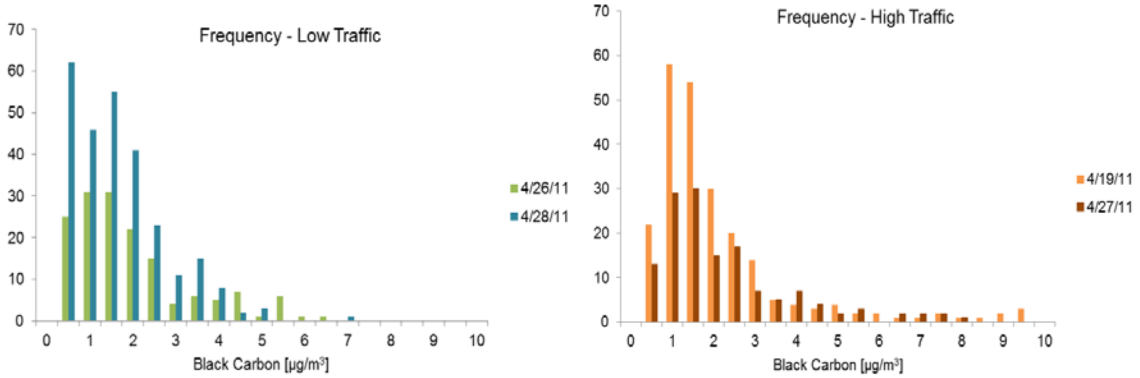

Figure 5a. Black carbon concentration distributions. Comparing frequency of concentrations between two low-traffic rides (left) and two high-traffic rides (right).

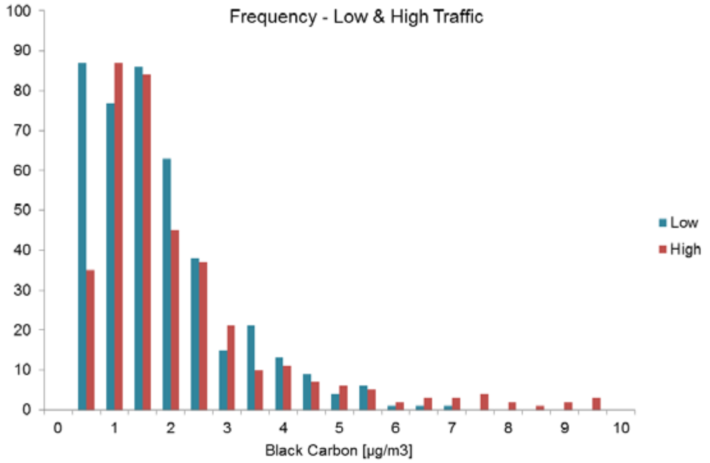

Figure 5b. Black carbon concentration distribution. Comparing frequency of concentrations between combined low-traffic data (average: 1.54 µg/m^3) and combined high-traffic data (average: 2.53 µg/m^3).

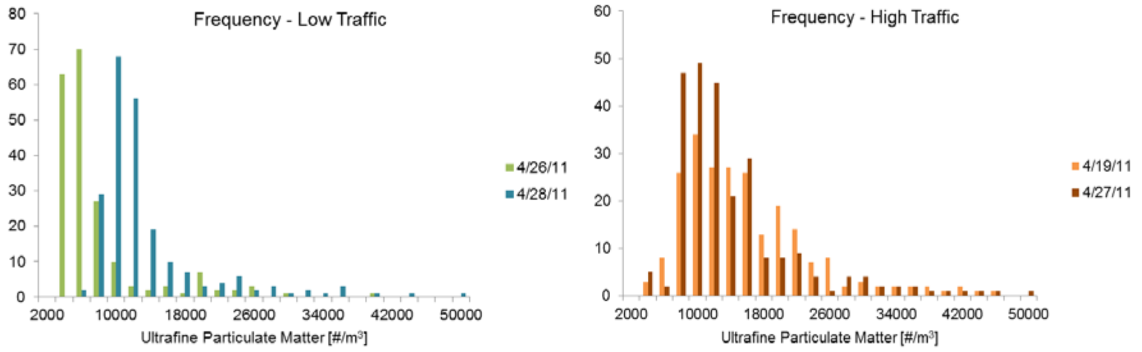

Figure 6a. Ultrafine particulate matter count distributions. Comparing frequency of particle counts between two low-traffic rides (left) and two high-traffic rides (right).

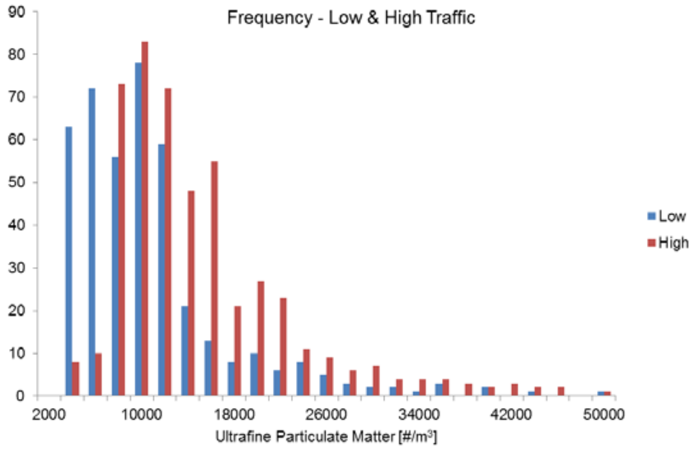

Figure 6b. Ultrafine particulate matter count distributions. Comparing frequency of particle counts between combined low-traffic data (average: 10,884 particles/m^3) and combined high-traffic data (average: 19,172 particles/m^3).

Lung Function Measurements

Spirometry measurements from all test days, including those with incomplete pollutant data, are summarized in Table 4. In total, there are six low-traffic measurements, and seven high-traffic measurements. The baseline averages had a wide range due to the different heights and weights of the subjects. The changes in spirometry parameters between the pre-cycling baseline and the post-cycling measurements, immediately afterward and delayed, were small for both the high and low traffic route.

For normal subjects, forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) changes within a day should not be considered statistically or biologically significant until they exceed 5% (Pelligrino et al., 2005). The largest change in FEV_1 was a 0.06 liter increase from a baseline average of 4.22 liters, a 1.4% positive change, while the largest change in FVC was a 0.06 liter decrease from a baseline average of 5.35 liters, a 1.12% negative change.

Table 4. Lung function measurements. FVC and FEV_1 are in liters.

	Average FVC ±SD	Average ΔFVC	Average FEV_1 ±SD	Average $ΔFEV_1$
Baseline Low Traffic	5.35 ±0.35	-	4.22±0.56	-
After Low Traffic	-	0.03	-	0.063
4-hour Low Traffic	-	-0.06	-	0.06
Baseline High Traffic	4.81±0.88	-	3.67±0.59	-
After High Traffic	-	-0.0257	-	0.06
4-hour High Traffic	-	-0.0471	-	0.04

DISCUSSION

Ambient Air Pollution Measurements

We found higher ambient concentrations of ultrafine particulate matter, black carbon, and carbon monoxide on the high-traffic route relative to the low-traffic route. Carbon monoxide measurements on both routes were all lower than the California Ambient Air Quality Standards of 10 mg/m^3 (8-hour average) and 23 mg/m^3 (1-hour average) (CARB, 2010). Air quality standards have not been established for ultrafine particulate matter or black carbon. We also found that ultrafine particulate matter concentration spikes occurred mainly at intersections. On the low-traffic route, the largest spikes occurred where the route crossed busy streets. Elevated ultrafine particulate matter and carbon monoxide were consistently measured on Oxford Street, and could be due to the current construction taking place on and near the road in addition to morning commute traffic. Spikes in particle count above 100,000 particles/cm^3 are comparable in magnitude to median concentrations measured on freeways with moderate-heavy diesel truck traffic (130,000 and 190,000 particles/cm^3, respectively) (Westerdahl, Fruin, Sax, Fine, & Sioutas, 2003). This supports our hypothesis that traffic volume is directly related to ambient pollutant concentrations and suggests that route choice can affect commuter exposure to pollutants associated with vehicle exhaust. These preliminary findings are consistent with previous studies comparing pollution exposure levels on routes of different ambient concentrations of air pollutants (Strak et al., 2010; McCreanor et al., 2007).

Exposure Measurements

Dose of inhaled air pollutants is a function of ambient concentrations and minute ventilation (ventilation rate in liters per minute), which was not accounted for in this study. This is especially important for cyclists because of their increased activity levels, which lead to increased ventilation. In a review of multiple European commuter exposure studies, de Hartog et al. (2010) found that the average ratios of car to cyclist pollutant exposures were greater than one for $PM_{2.5}$, elemental carbon, and ultrafine particulate matter, meaning that the measured ambient concentrations of those pollutants were higher inside vehicles than they were on bicycles. However, studies that accounted for activity level found that cyclists' minute ventilation was approximately double that of car passengers, leading to overall higher inhaled doses of pollutants (Zuurbier et al, 2010). Additionally, the fraction of inhaled particulate matter that stays in the respiratory tract can be estimated using a deposition factor (DF), which varies based on particle size and inhalation volume. This is particularly relevant to the discussion of ultrafine particulate matter, as its DF is higher than that of larger particles (Int Panis et al., 2010).

Health Effects of Increased Pollutant Exposure

Although we did not find significant changes in pulmonary function after cycling on either route, there is research that supports various relationships between traffic volume, pollutant exposure, and health. Commuter exposure studies have demonstrated negative health impacts associated with increased pollutant concentrations in asthmatic study subjects (McCreanor et al., 2007), though these findings were not reproduced in studies with non-asthmatic study subjects (Strak et al., 2010). However, after factoring in the benefits of increased physical activity, estimated to be approximately nine times larger than the risks, bicycle commuting has a net positive impact on health (de Hartog et al., 2010). Our findings were not unexpected given a healthy study population and short exposure time, but they likely do not accurately represent the potential health effects of traffic volume and emissions for a population with a broader range of pre-existing health conditions and long-term exposure to commute-related air pollution.

Limitations

The major limitations of this study were sample size and time-span. Using data from eight study subjects riding two six-mile routes over the course of two weeks, it is difficult to make broad conclusions about commuting exposures in Berkeley. Moreover, participant exclusion on the basis of age, asthma, smoking, and pre-existing respiratory/cardiac conditions prevents the study population from being representative of the true Berkeley population. This may hold implications for the generalizability of the health outcome measurements in this study to the broader, more heterogenous population. Similarly, data collected over a short time span does not allow me to account for the large temporal and seasonal variations in air pollutant concentration and dispersal or for the effects of chronic exposure to ambient air pollutants.

Future Research

This study is still in progress, and next steps include collecting more data for all pollutants, especially nitric oxide and $PM_{2.5}$, and analyzing heart rate variance data. The small scale of this study provides many opportunities to expand and improve future study designs. Potential next steps could include repeating exposure and health measurements with an asthmatic or elderly study population, over a longer time period, or in a more heavily polluted location. Recruiting a larger study population representing a broader spectrum of health status would be a good next step to expand and refine the results of this study.

Broader Implications

This study contributes to the growing body of literature that investigates the relationships between active transport, ambient air pollution, and public health. A shift from vehicle use to active transportation would help reduce traffic volume and related emissions (including climate active pollutant) and improve public health through increased exercise. Short trips (under three miles) in particular have been identified as a good target for this travel mode shift; reducing vehicle miles traveled in the United States by 0.8-1.8% would save an estimated 20,000-46,000 tons of CO_2 equivalent of exhaust emissions nation-wide (de Nazelle, Morton, Jerrett, & Crawford-Brown, 2010).

The benefits of active transportation must be weighed against the risks. The results from my study indicate that choosing low-traffic routes such as Berkeley's Bicycle Boulevards and residential roads can reduce the risks associated with pollutant exposure. This information is useful for individuals to incorporate into their commuting decisions and for health practitioners to factor into exercise recommendations. Lower exposures associated with low traffic routes may eventually support changes to the built environment (city, building, and street design) that allow for healthier and safer routes for active transportation. Other risks of active commuting such as noise and UV exposure, collisions, and accidents are also likely targets for modifications and improvements. A shift away from vehicle travel is consistent with the goals of California's Sustainable Communities and Climate Protection Act (Senate Bill 275), which calls for the reduction of greenhouse gas emissions through sustainable land use, housing, and transportation (California Environmental Protection Agency, 2010b).

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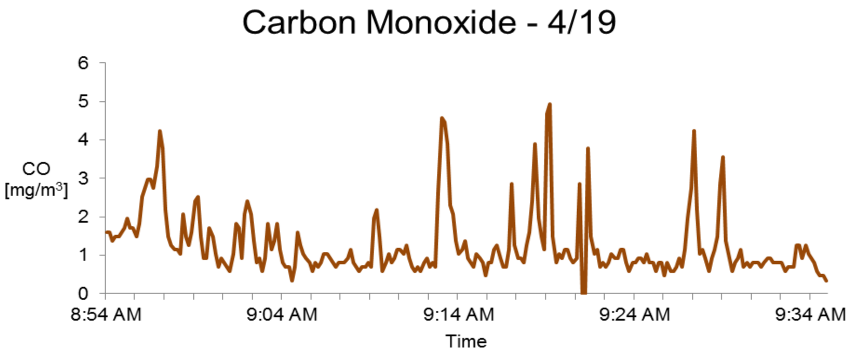
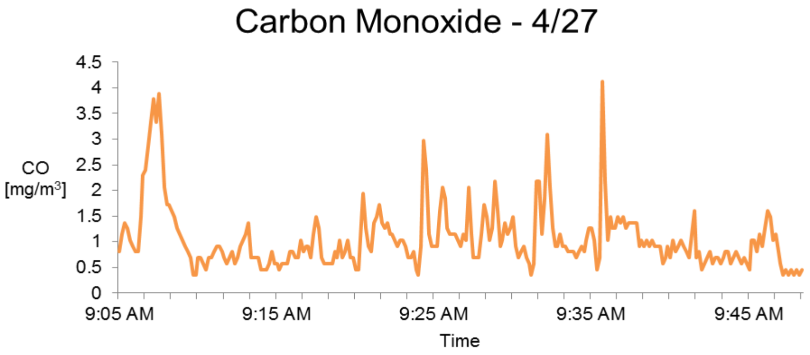
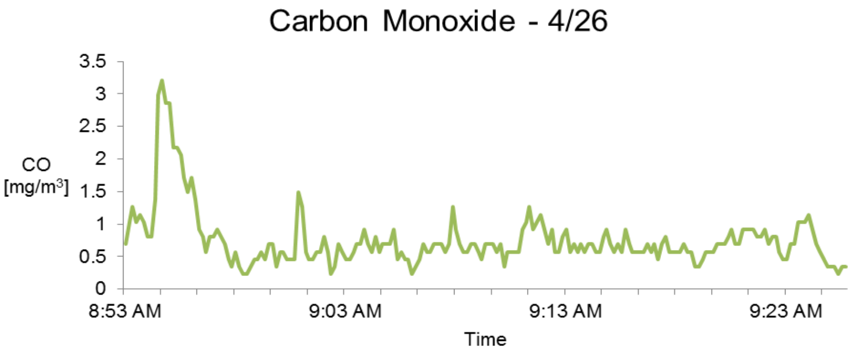
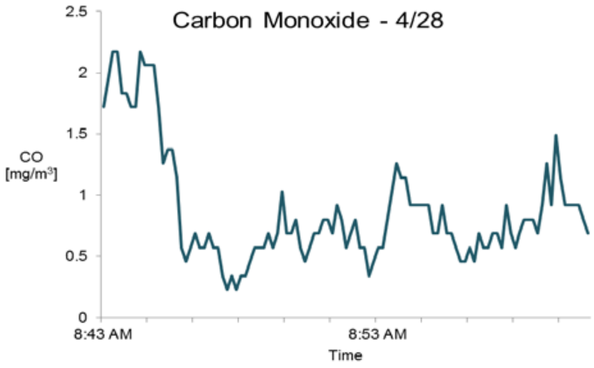
APPENDIX


Carbon Monoxide - 4/19


Carbon Monoxide - 4/27


Carbon Monoxide - 4/26


Carbon Monoxide - 4/28