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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.

In addition to the continuous instruments, ambient air was sampled over segments of 20–30 min through stainless steel adsorption/thermal desorption (ATD) cartridges (Tenax TA plus Carbotrap 1TD) as in Pankow et al. (2011). Each cartridge was thermally desorbed and analyzed for VOCs using a gas chromatograph and mass spectrometer (see Pankow et al. (1998)). Every sample was analyzed on the day collected. Sample concentrations were determined for 75 target compounds, with corrections for travel and lab blanks (with a detection limit of 0.5 μg/m^3).

The three air sampling devices were co-located at the front of the bicycle: ATD cartridges were attached to the handlebars of the bicycle at a height of 1.0 m, the TVOC inlet was at a height of 1.1 m and the CO sensor was at a height of 0.8 m. Breathing zone heights for three bicyclists who operated bicycles during data collection were 1.5–1.6 m.

High-resolution concentrations of BTEX compounds (benzene, toluene, ethylbenzene, and xylenes) were estimated by disaggregating the segment-level VOC data using the TVOC measurements. The BTEX concentration at time t on segment s; was calculated as

$$C_{t,s} = \frac{\mathrm{TVOC}_{t,s}}{\overline{\mathrm{TVOC}}_s}\overline{C}_s$$

where $\overline{C}_s$ and $\overline{\mathrm{TVOC}}_s$ are the mean BTEX and TVOC concentrations on segment s, respectively, and $\mathrm{TVOC}_{t,s}$ is the measured TVOC concentration at time t on segment s. This approach uses the variability information in the TVOC data with the compound-selective concentration information in the segment-level VOC data. The main assumption is that on-road variation in TVOC is representative of BTEX variation. This disaggregation is likely conservative with respect to sub-segment-level BTEX variability due to the predominance of vehicular sources of BTEX compounds.

Temperature and humidity were measured on-road with a HOBO U12 (Onset, Bourne, MA), logged at 1 Hz. Wind data were retrieved from an Oregon Department of Environmental Quality monitoring station in the data collection area (Station SEL 10139). Wind data were scalar average wind speeds at five minute aggregation, measured by an anemometer at a height of 10 m.

Roadway data

Average daily traffic (ADT) estimates were available for street links throughout the City of Portland through a GIS layer obtained from the Portland Bureau of Transportation (PBOT). The ADT data set was created by PBOT in 2005 by interpolating Monday–Thursday count data from the previous 5 years (prioritizing more recent counts and excluding counts with inconsistent volumes). The ADT data were validated with 51 locations for which additional recent counts were available (2008–2012). The validation results were good, with a correlation coefficient of 0.99, mean percent error of 1.1% and mean absolute percent error of 16.4%. Two additional GIS data sets were obtained from Metro (the metropolitan planning organization for Portland, Oregon) through the Regional Land Information System: transportation system plan (TSP) and bicycle network link classifications.

GPS receivers recorded 1 Hz location data. Redundant GPS devices and on-bicycle video were used to cross-check the location data. The GPS-based location data points were mapped onto GIS roadway network links based on proximity (out to 15 m), with manual and scripted corrections at cross-streets and coincident roadways (e.g. parallel paths and overpasses). Of the 104,291 GPS data points with non-missing longitude and latitude fields, 90%, 55%, and 84% were mapped to the TSP, bicycle network, and ADT GIS layers, respectively. Un-matched data points were due to locations off the network (e.g. the bicycle network layer only includes links for bicycle facilities) or inaccuracy in the GPS data. During 255 km of on-road sampling, 150 unique km of roadway were sampled; the 50th, 95th, and 99th percentile link sampling frequencies were 1, 5, and 10, respectively. The location data were assigned to facility/roadway type categories using information in the matched TSP and bicycle network data sets. The road type classifications and ADT for sampled links are mapped in Fig. 1.

Off-street riding locations included paths in Mt Tabor City Park and designated off-street paths in the bicycle network. Most of the off-street paths in the bicycle network run parallel to roadways with motorized vehicle traffic at distances of 40–200 m; off-street paths in Mt Tabor City Park are located 300–700 m away from major roadways. The main sampled off-street paths in the bicycle network were the I-205 Path and the Springwater Path. The I-205 Path runs north–south parallel to a freeway with high ADT (100,000–150,000). The path is ~100 m from the edge of the freeway, but frequently behind a berm or sound wall which can reduce on-path exposure (Moore et al., 2011; Ning et al., 2010). The Springwater Path runs east–west between the Willamette River and the I-205 Path with sections in parkland, residential areas, and an industrial corridor. VOC-emitting businesses in the industrial corridor include metal casting and machining, engine services, paint and powder-coating, and other manufacturing. Observations collected within the geographic bound of the industrial corridor were identified as shown in Fig. 2 (a distance of 2.5 km along the path). The subset of observations through the corridor comprises 1% of the dataset.

The ADT data represent the average spatial distribution of motor vehicle traffic on the street network. Dynamic (time varying) traffic data for the entire network were not available, so continuous traffic data from two control locations were used to represent the temporal distribution of traffic during sampling. Ten-second traffic data at two locations on a major arterial in the study area were obtained from PBOT. Vehicle counts and speeds in each lane were collected with Digital Wave Radar (DWR) sensors at mid-block locations. Traffic density (vehicles per length of roadway) was calculated from speed and

(a)

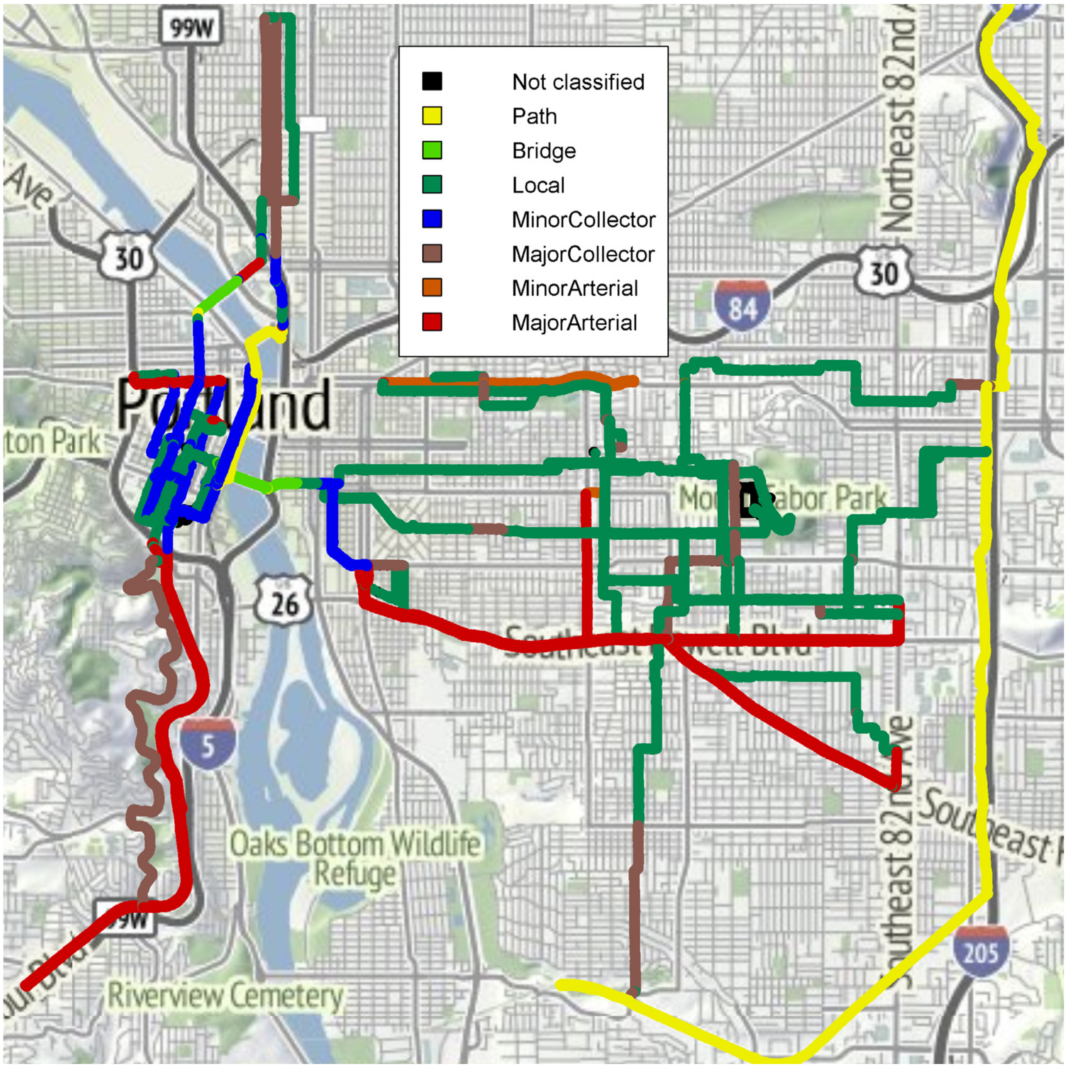

Fig. 1. Classification (a) and ADT (b) for sampled facilities (background image from OpenStreetMap).

volume data. The dynamic traffic variables were applied to samples collected throughout the network to account for the diurnal variability of traffic levels.

Results

Regression model of BTEX exposure

A model of 5-s BTEX exposure concentrations was estimated using ordinary least squares with heteroscedasticity and autocorrelation consistent (HAC) standard errors. The dependent variable was natural log-transformed to improve normality of the residuals. The statistical software R was used for analysis; the packages "sandwich" and "lmtest" were used to estimate HAC standard errors with the pre-whitened covariance matrix from Andrews and Monahan (1992). Concentration data from the pre-ride period were excluded from model estimation, but data collected while riding on off-street paths in Mt Tabor City Park after the pre-ride period were included. The following explanatory variables were tested by stepwise addition to the model:

- Background concentration measured at Mount Tabor City Park during a pre-ride half-hour period.
- Temperature and humidity measured on-road and wind speed measured at the nearest fixed-site air quality monitoring station (SEL 10139).

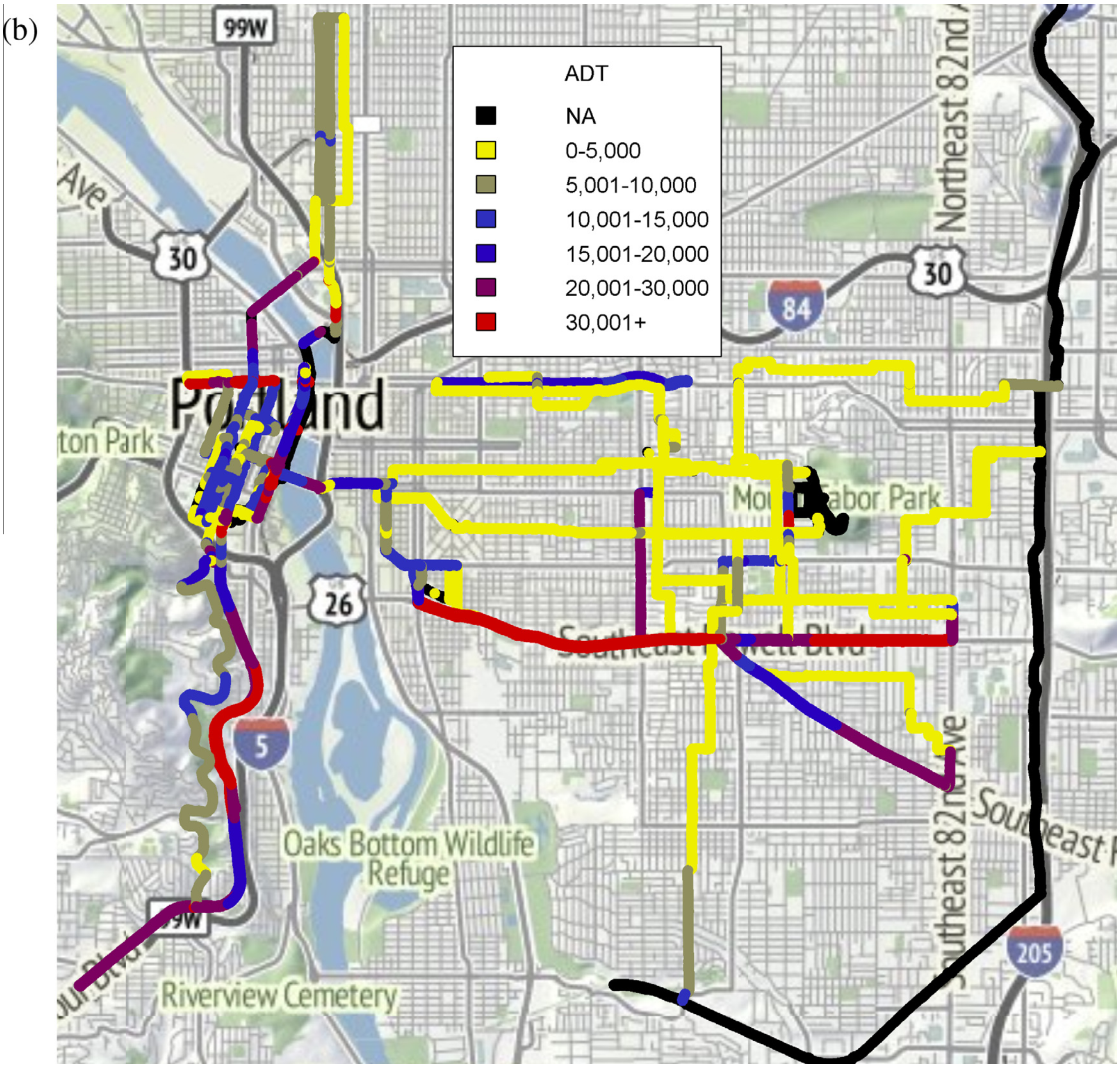

Fig. 1 (*continued*)

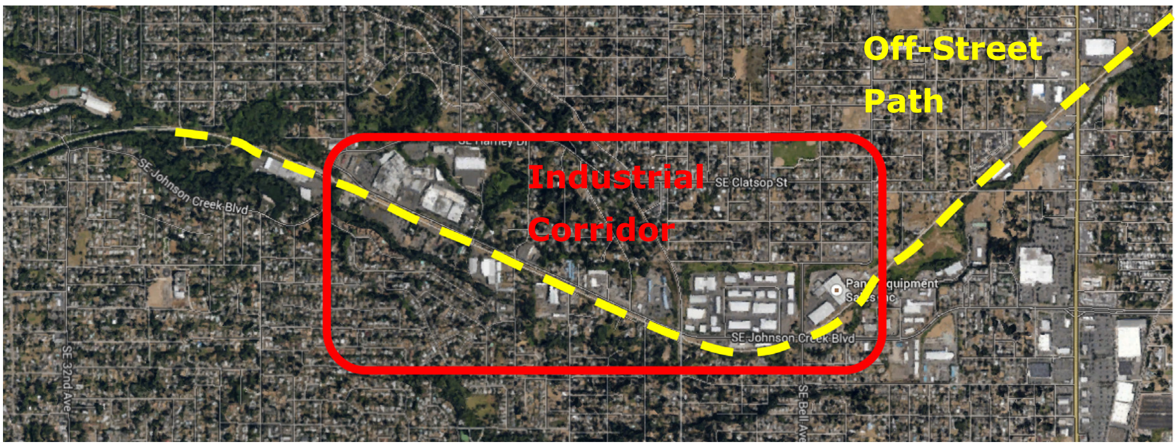

Fig. 2. Industrial corridor along the off-street path.

- Location/facility dummy variables (on-street without bicycle lane as the reference level): on-street with bicycle lane, off-street path (all off-street facilities combined), off-street path in network (off-street paths designated in the bicycle network), off-street path in park (off-street paths in Mt Tabor City Park), and Industrial corridor (note: some of these dummy variables are subsets of others).
- Average daily traffic.
- Continuous traffic speed, volume, and density at reference locations.
- Road grade.
- Intersection (proximity to major road crossing as a continuous variable and a dummy variable for <25 m).
- Stop-and-go riding: dummy variables for a stop (due to traffic signals, stop signs, traffic congestion, etc.), the first 10 s after a start, low-speed riding (>0 and ⩽12 kph), or a combination of these conditions.

The real-time traffic variables (speed, volume, density) were correlated among each other, as were weather variables. BTEX and CO background concentrations were correlated with weather variables, as expected. Linear correlation coefficients among select explanatory variables and exposure concentrations are shown in Fig. 3. BTEX and CO concentrations had generally low correlation (<0.4) with all explanatory variables.

The tested explanatory variables were retained if their associated model coefficients were statistically significant at $p < 0.05$ (the same criterion was used to remove previously-added variables not jointly significant with the added variable). Due to correlations among background concentrations, weather variables, and dynamic traffic variables, the order of stepwise variable testing influenced the retained variables. Different variable sequences were tested to generate candidate final models in which all variable coefficients were statistically significant at $p < 0.05$. Candidate final models were compared and a preferred model selected based on consideration of Akaike Information Criterion (AIC), adjusted R^2, and stability of parameter estimates. Alternative specifications are discussed in the next section.

The preferred model estimated coefficients with HAC robust standard error estimates are shown in Table 1 ($N = 13{,}074$, adjusted $R^2 = 0.29$). Summary data on measured concentrations and the explanatory variables in the preferred model are shown in Table 2. Analysis of the model residuals shows both autocorrelation and heteroscedasticity, justifying the need for HAC standard error estimates. The first-order autocorrelation coefficient for the residuals is 0.833, and a Box–Ljung test is significant at $p < 0.01$. The model residuals exhibit significant heteroscedasticity by facility type ($p < 0.01$). Background concentrations are the strongest single explanatory variable in terms of explained variance, followed by Transport facility and ADT.

Neither a single combined "Off-street path" dummy variable nor a separate dummy variable for "Off-street path in network" was statistically significant at $p < 0.05$. In other words, concentrations for off-street paths in the bicycle network were not statistically different from concentrations for a zero-ADT on-street facility. However, exposure for on-street facilities was higher than off-street paths because all on-street facilities had ADT > 0 and the contribution of ADT is positive. "Off-street path in park" was significantly lower, presumably because the distance to motorized traffic was several times larger than for "Off-street path in network". Without ADT variables in the model, the "Off-street path" coefficient would be −0.152 ($p < 0.001$).

The exposure model coefficients in Table 1 show that background, wind, roadway, and travel variables are all determinants of on-road exposure. The elasticity of on-road to background BTEX concentrations was 0.54. Concentrations decreased 17% with each 1 m/s increase in wind speed. The dummy variable coefficients in Table 1 can be interpreted[3] as expected BTEX concentrations for an off-street path in a park 19% lower than an off-street path in the bicycle network or a zero-ADT on-street facility, and concentration increases of 350% in the industrial corridor and 24% in stop-and-go riding (diminishing with increasing ADT, due to the interaction term).

The total effect of ADT on BTEX exposure is the combination of linear, squared, and interaction terms in the model. Fig. 4 shows modeled BTEX exposure concentrations with 95% confidence bands as a function of ADT for on-street transportation facilities, with and without Stop-and-go riding conditions. Mean background concentration and wind speed are applied (from Table 2). On-street exposure increases with ADT. The effect of Stop-and-go riding disappears at high ADT as the confidence bands fully overlap. Fig. 4 also includes modeled exposure for an off-street path in the bicycle network and in the park. The modeled concentration on off-street path in network is the same as a zero-ADT on-street facility; the modeled concentration on the off-street path through the industrial corridor (29 $\mu g/m^3$) is dramatically higher (not shown). This finding emphasizes the potentially important role of near-facility, non-traffic sources of BTEX compounds.

Alternative specifications

ADT is a strong predictor of exposure and a useful, accessible parameter to apply in practice. Several specifications of ADT in the model were explored to provide more insight into its relationship with BTEX exposure. Table 3 compares similar models with three different ADT specifications: linear, quadratic, and logarithmic. The specifications are similar to the full model

[3] Elasticity interpretations for dummy variables are more complicated than for continuous variables because dummy variables are not differentiable. An estimator for the effects of dummy variables on the dependent variable in a log-linear model is $\left[\exp(\beta - \frac{1}{2}SE_\beta^2) - 1\right]100\%$, where β is the estimated dummy variable coefficient and SE_β is its standard error (Jan van Garderen and Shah, 2002).

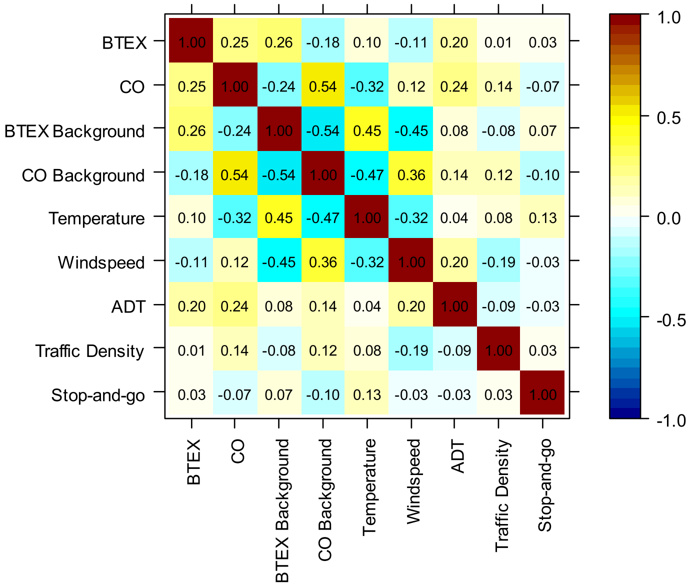

Fig. 3. Linear correlations among 5-s aggregated explanatory variables and exposure concentrations.

Table 1
5-s BTEX exposure model[a] estimated coefficients.

	Value	Standard error	p-Value	Explained variance[b]
Intercept	1.196	0.144	<0.001	–
ln(BTEX background)	0.541	0.076	<0.001	52%
Wind speed (m/s)	−0.172	0.022	<0.001	4%
Off-street path in park (0, 1)	−0.213	0.050	<0.001	11%
Industrial corridor (0, 1)	1.552	0.278	<0.001	8%
Stop-and-go (0, 1)	0.213	0.031	<0.001	3%
ADT (1000 veh/day)	0.0303	0.0050	<0.001	20%
ADT^2	−0.00036	0.00012	0.004	2%
ADT: Stop-and-go	−0.0060	0.0025	0.017	<1%

[a] Dependent variable: natural log-transformed BTEX concentration (μg/m^3).
[b] Percent reduction in modeled sum of squares due to removal of each model term *ceteris paribus*.

Table 2
Characterization of pollutant concentrations and explanatory variables.

	Minimum	Median	Mean	Maximum
BTEX (μg/m^3)	0.48	6.57	10.29	1020.00
BTEX background (μg/m^3)	1.82	4.63	5.54	11.18
CO (ppm)	0.00	0.48	0.56	20.17
CO background (ppm)	0.07	0.15	0.37	0.77
Temperature (C)	10.9	19.0	18.7	26.4
Wind speed (m/s)	0.18	1.74	1.84	4.11
ADT for on-street facilities (vehicles/day)	116	2874	12,340	53,950
Traffic density (vehicles/lane-mile)	12.9	19.0	20.7	40.2
Off-street path	26% TRUE			
Industrial corridor	1% TRUE			
Stop-and-go	13% TRUE			

described in the previous section, with the interaction term removed and estimated using only data from on-street transportation facilities. All coefficients are significant at $p < 0.05$ based on HAC robust standard error estimates.

Fig. 5 illustrates the effects of ADT on BTEX exposure for the model specifications in Table 3; note that Fig. 5 gives arc semi-elasticity while the model coefficient estimates provide point semi-elasticity. By visual inspection, 2% per 1000 ADT appears to be a good central estimate for semi-elasticity across model specifications (Fig. 5 also includes a line representing this fixed semi-elasticity). The point semi-elasticity from the linear model is a 1.5% increase in BTEX exposure per 1000 ADT. The point semi-elasticity from the quadratic model falls from 3.0% per 1000 ADT at 1000 ADT to 1.4% per 1000 ADT at 40,000

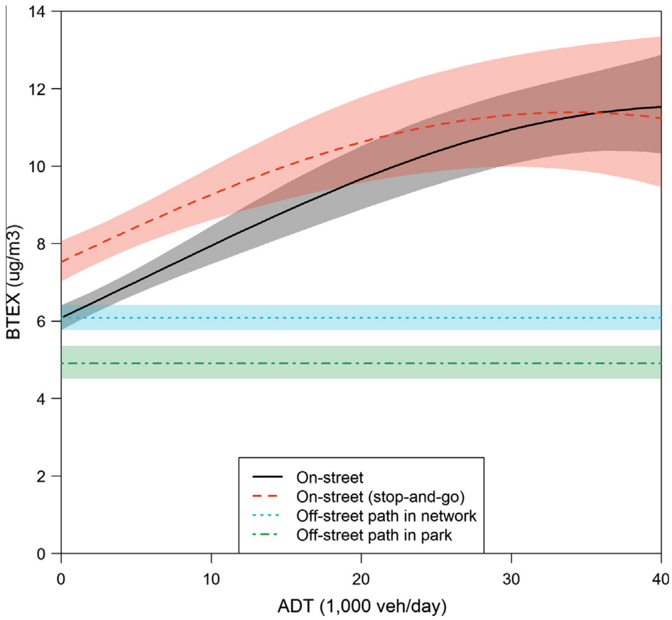

Fig. 4. Modeled effects of ADT and facility on BTEX exposure (shaded area is 95% confidence bands).

Table 3
Alternative specifications of ADT variable in 5-s BTEX model.[a]

	Linear	Logarithmic	Quadratic
Intercept	1.382	0.379	1.297
ln(BTEX background)	0.486	0.523	0.502
Wind speed (m/s)	−0.202	−0.192	−0.196
Stop-and-go (0, 1)	0.159	0.142	0.146
ADT (1000 vehicles/day)	0.0149	–	0.0305
ADT^2	–	–	−0.000392
ln(ADT)	–	0.135	–
Adjusted R^2	0.254	0.263	0.261
AIC	20,244	20,126	20,143

[a] Dependent variable: natural log-transformed BTEX concentration (μg/m^3); only on-street data used in estimation.

ADT. The logarithmic model implies BTEX exposure elasticity to ADT of 0.14, which aligns with the semi-elasticity in the linear model at an ADT of 9000. The quadratic ADT specification was selected for the preferred model because the estimated coefficients were more consistent with changing specifications than the logarithmic ADT specification.

ADT effects were also tested by adding 26 dummy variables for each individual street name (an attribute from the TSP GIS layer) with at least 2 min of on-road data. The estimated ADT coefficients in this model still indicate an approximate 2% increase in BTEX exposure per 1000 ADT, suggesting that the estimated effect of ADT is robust to the influence of specific streets. Other specifications of the location/facility dummy variables were also tested, for example a unique dummy variable for the off-street path parallel to a freeway. However, after controlling for ADT, facility type-specific estimated coefficients were not significantly different from one another. More specifically, exposure levels on the path parallel to the I-205 freeway were *not* significantly higher than on the other off-street paths parallel to arterial streets ($p = 0.40$). The lack of elevated exposure on the I-205 path is likely due to greater distance from the roadway and shielding with physical barriers. Presence of a bicycle lane for on-street riding is only significant without ADT in the model (coefficient of 0.292, $p = 0.02$); without ADT bicycle lanes are proxies for higher-traffic roadways.

Although static roadway variables (ADT, facility type) were strong determinants of BTEX exposure, the dynamic traffic variables tested (speed, volume, density) were not significant. This result could be due to correlation between traffic conditions and meteorology/wind speed (Fig. 3) or to the dominance of spatial over temporal variability in traffic (especially for consistent times of the day). In other words, the variation in bicyclist exposure at one location (due to dynamic traffic conditions) is smaller than the variation over the course of a ride (due to travel on facilities of varying ADT).

Individual stop-and-go dummy variables (stop, startup, and low-speed riding) were not significantly different from each other. The combined "Stop-and-go" dummy variable represents the higher exposure levels experienced when a bicyclist

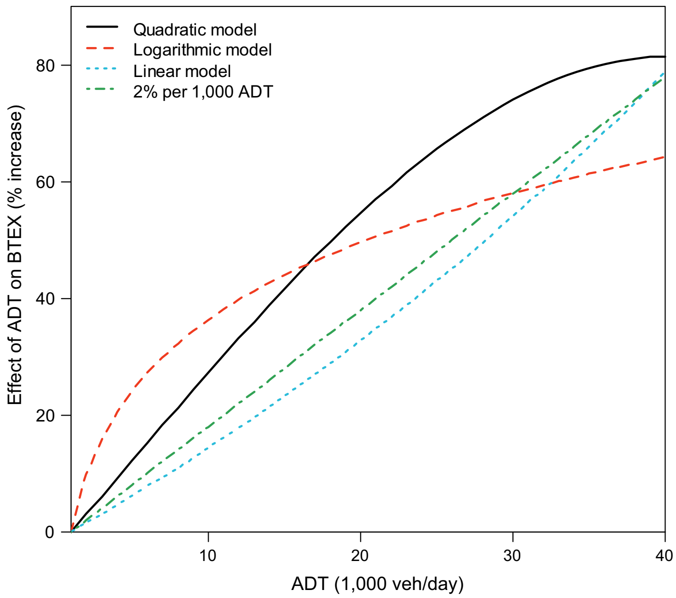

Fig. 5. ADT effects on BTEX exposure for three different model specifications (Table 3).

stops due to congestion or due to an intersection. "Intersection" was not significant in the model when stop-and-go variables were included, likely because the dynamic travel variables capture intersection effects (where traffic volumes and motor vehicle emissions rates are higher). Intersection and Stop-and-go have a linear correlation coefficient of 0.23. Replacing Stop-and-go with an Intersection dummy variable (25 m buffer around major road crossing), the overall model fit is lower but the dummy variable coefficient is similar: 0.179 ($p = 0.001$), implying 19% higher concentrations around intersections. The known effect of grade on motor vehicle emissions rates did not lead to a significant grade variable in the model. Both temperature and humidity were tested and found to be not significant at $p < 0.05$ with background concentrations in the model.

A model was estimated using 5-s TVOC data as an alternative dependent variable, in order to provide a reference for future studies using a PID for on-road sampling (without the more complex and costly GC/MS analysis required for isolation of BTEX compounds). The TVOC model was developed using the same method described in the previous section for the BTEX model, testing all available explanatory variables. The estimated model is shown in Table 4 ($N = 13{,}075$, adjusted $R^2 = 0.19$). The roadway variable coefficients are similar to the BTEX model in Table 1; the estimated ADT effect is similar to the linear model in Table 3. Background concentrations have a smaller effect on TVOC exposure in Table 4 than they do on BTEX exposure in Table 1, possibly due to a higher proportion of biogenic VOCs at the park (included in TVOC but not BTEX concentrations).

Regression model of CO exposure

A model of natural log-transformed CO concentrations was also estimated using OLS with five-second aggregated data and HAC robust standard errors. The CO model specification was developed as described in Section 'Regression model of BTEX exposure', testing all available explanatory variables. The estimated model is given in Table 5 ($N = 15{,}846$, adjusted $R^2 = 0.40$). Compared to the BTEX model in Table 1, the explained variance of background concentrations is higher and of ADT is lower. This difference could be due to the longer atmospheric lifetime of CO than aromatic VOCs (Atkinson, 2000; Seinfeld and Pandis, 2012).

The ADT coefficient in Table 5 is similar to that of the linear ADT specification for BTEX in Table 3, and is well-represented by a semi-elasticity of exposure of 1.5% per 1000 ADT. The effect of Traffic density at the control locations (i.e. temporal variability in traffic levels) is significant and positive for CO, whereas the Stop-and-go and Intersection variables (in any configuration) are not significant at $p < 0.05$. The interaction of ADT and Traffic density is also not significant ($p = 0.36$). Similar to the BTEX model, after controlling for ADT "Off-street path in network" is not significant.

Dynamic traffic density was collected at control locations and represents variation in traffic over the sampling period. Thus, the magnitude of the model coefficient for Traffic density in Table 5 should not be interpreted as an elasticity of exposure to concurrent traffic density on each street. The significant positive coefficient indicates that CO exposure is higher during higher-traffic time periods, after controlling for ADT (i.e. the spatial distribution of traffic). It is not clear whether the effect of the Traffic density variable is due to varying traffic on the sampled street or more broadly varying traffic levels or congestion around the city. Importantly, the estimated ADT coefficient was not impacted by the inclusion of the Traffic density variable, indicating that the estimated effect of ADT is robust to diurnal traffic congestion variability.

Table 4
5-s TVOC exposure model[a] estimated coefficients.

	Value	Standard error	*p*-Value	Explained variance[b]
Intercept	2.234	0.251	<0.001	–
ln(TVOC background)	0.079	0.026	0.002	11%
Wind speed (m/s)	−0.059	0.021	0.004	<1%
Temperature (C)	−0.029	0.013	0.023	3%
Off-street path in park (0, 1)	−0.189	0.059	0.001	17%
Industrial corridor (0, 1)	1.904	0.270	<0.001	22%
Stop-and-go (0, 1)	0.136	0.029	<0.001	3%
ADT (1000 vehicles/day)	0.016	0.002	<0.001	44%

[a] Dependent variable: natural log-transformed TVOC concentration (ppb).
[b] Percent reduction in modeled sum of squares due to removal of each model term *ceteris paribus*.

Table 5
5-s CO exposure model[a] estimated coefficients.

	Value	Standard error	*p*-Value	Explained variance[b]
Intercept	0.077	0.192	0.689	–
ln(CO background)	0.635	0.032	<0.001	75%
Wind speed (m/s)	−0.083	0.024	<0.001	1%
Temperature (C)	−0.047	0.007	<0.001	6%
Off-street path in park (0, 1)	−0.241	0.049	<0.001	5%
Industrial corridor (0, 1)	1.581	0.243	<0.001	3%
ADT (1000 vehicles/day)	0.012	0.002	<0.001	5%
Traffic density (vehicles/lane-mile) at reference location	0.028	0.004	<0.001	4%

[a] Dependent variable: natural log-transformed CO concentration (ppm).
[b] Percent reduction in modeled sum of squares due to removal of each model term *ceteris paribus*.

Although there are no previously-reported ADT effect models with which to compare these results, median exposure differences in previous studies of bicyclists on high-traffic versus low-traffic routes were 102% for VOC and 47% for CO (Bigazzi and Figliozzi, 2014). Those exposure effects would be expected for ADT differences of 47,000 for BTEX (linear model in Table 3) and 32,000 for CO (Table 5) – both reasonable ADT differences for high-traffic arterials vs. low-traffic local streets.

Conclusions

This paper provides the first multi-pollutant quantification of the relationship between bicyclist exposure and facility ADT, and is the first study to quantify VOC exposure differences by facility type. Semi-elasticity of BTEX, TVOC, and CO exposure to ADT was around 2% per 1000 ADT, robust to several different model specifications. BTEX exposure was approximately 20% higher around intersections and during stop-and-go riding conditions. Exposure on off-street facilities varied widely; high exposure was coincident with near-path industrial land use.

One limitation of this study is that ADT is an imperfect measure of traffic volume during sampling. In addition, vehicle classification data (i.e. truck fractions) were not available throughout the network. Dynamic traffic data from control locations were used in an attempt to account for diurnal traffic variability. Although more precise traffic data could improve the precision of the models, ADT was of primary interest as the most widely-available roadway descriptor. Another limitation of this study is the temporal sampling coverage; longitudinal studies using stationary monitors could be used to extrapolate the findings. Some correlation is expected among concentrations of traffic-related pollutants, but the impact of facility ADT on bicyclist exposure to other toxicants such as particulate matter and NO_2 remains to be quantified and should be the focus of future research efforts.

Because of the route orientation of study objectives, only near-road and weather variables were included in the models; land use regression was outside the scope and is left for future work. In particular, more work is needed to determine the attributes of off-street paths and surrounding environment that most influence exposure. As in any regression model, there may be some correlation between variables included in the model and omitted variables (e.g. correlation between adjacent land use or roadway cross-section and ADT). Hence, results should be applied with caution in other cities and additional research is needed to generalize the results.

The findings in this paper have clear policy and design implications. Roadway characteristics strongly influence bicyclists' exposure concentrations, and ADT seems to be a parsimonious approach to characterize the impact of on-street facilities on exposure. The quantitative estimates of the ADT effect on exposure provide a ready tool for analysts to calculate expected differences in exposure levels among routes. Route-level exposure differences can be used for both planning and routing applications (Hatzopoulou et al., 2013a; Hertel et al., 2008; Sharker and Karimi, 2013). The findings support the idea that provision and usage of low-traffic bicycle routes in residential areas is an effective way to reduce bicyclists' exposure. Avoiding high-volume intersections is also an effective way to reduce bicyclists' exposure. Increasing lateral separation from motor vehicle traffic can also reduce bicyclist exposure (Grange et al., 2014; Kendrick et al., 2011; MacNaughton et al., 2014). Even if aligned parallel to a high-volume freeway, off-street paths can provide low-exposure routes if sufficiently separated and/or shielded from traffic. Bicyclists using off-street paths through industrial areas can experience exposure concentrations higher than most on-street facilities; to design low-exposure routes separation should also be provided between industrial sources and off-street paths.

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