1-2015

Roadway Determinants of Bicyclist Multi-pollutant Exposure Concentrations

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Submitted to the 94th Annual Meeting of the Transportation Research Board
January, 2015

Revised: November 7, 2014

5,257 + 8 (figures+tables) x 250 = 7,257 words

ABSTRACT

Due to poorly quantified traffic-exposure relationships, 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 characteristics on bicyclist multi-pollutant exposure concentrations, controlling for meteorology and background conditions. Concentrations of volatile organic compounds (VOC), carbon monoxide (CO), and fine particulate matter ($PM_{2.5}$) are modeled using high-resolution on-road data. This paper also compares exposure differences on immediately parallel high-traffic/low-traffic facilities and is the first study to quantify VOC exposure differences by facility. 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 increased by around 2% per 1,000 ADT, robust to several different regression model specifications. The results have important 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-pollution facilities. Direct comparisons of exposure concentrations on parallel routes shows that minor detours to nearby low-traffic facilities can dramatically reduce exposure to strongly traffic-related pollutants.

1 INTRODUCTION

While more than 40 studies have measured bicyclist pollutant exposure concentrations, studies including intra-modal covariates are still lacking *(1)*. Several studies have tested the effects of specific facility types and found lower concentrations on more separated bicycle infrastructure *(2–4)*. A few studies have also tested high-traffic versus low-traffic bicycle routes, finding significant differences in exposure *(5–7)*. High-traffic vs. low-traffic differences are typically larger for the more strongly traffic-related pollutants such as volatile organic compounds (VOC), ultrafine particles (UFP), carbon monoxide (CO), and black carbon particulate matter (BC) *(1)* .

But bicyclist exposure research frequently fails to find significant associations between more specific traffic variables and exposure *(4, 8–11)*. Hatzopoulou et al. *(4)* found significant increases in BC exposure of 0.8-1.5% with hourly diesel vehicle (truck and bus) counts, and Kaur and Nieuwenhuijsen *(9)* found 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 modes has quantified some effects of traffic volumes on travelers' exposure *(12, 13)*, 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, CO, and $PM_{2.5}$ (fine particulate matter) is quantified. Models of exposure are estimated from measured on-road data using roadway and traffic variables while controlling for weather and background concentrations. In addition, concentration differences between parallel high-traffic and low-traffic routes are quantified.

2 DATA COLLECTION

On-road concentration measurements were carried out in Portland, Oregon, on nine days in April through September, 2013. All on-road data collection was performed near the morning peak travel period (7:00-10:00 hr). A pre-ride period of 30 minutes at a low-concentration starting location (a 0.8 km^2 park) was used to measure reference background concentrations. A variety of roadway facilities were selected for prescribed sampling routes, including off-street paths and mixed-use roadways ranging from local roads to major arterials. Four sets of paired parallel facilities were sampled repeatedly to measure exposure differences of minor detours (see Section 3.4).

2.1 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.

1. **Total volatile organic compounds (TVOC)**: TVOC concentrations were measured using the PhoCheck Tiger (IonScience, Cambridge, UK). The Tiger measures TVOC using a photoionization detector (PID) with a 10.6 eV lamp, which detects compounds with an ionization potential below 10.6 eV. Individual compounds within that range 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 hours. 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 our knowledge. Earlier models of the PhoCheck were used for air quality studies in motor-vehicle environments *(14–16)*. 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. Adjusted TVOC values were calculated as the raw TVOC readings minus a zero reference curve based on the carbon filter zero-readings. The zero-reading points were removed for analysis, as were the first 15 min after the instrument was turned on (the warm-up period suggested by the manufacturer).
2. **Carbon monoxide (CO)**: 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 to 200 ppm and a resolution of 0.05 ppm. It is commonly used for ambulatory CO measurements *(1, 17)*. 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.
3. **Particulate matter (PM)**: $PM_{2.5}$ concentrations were measured using the P311 laser particle counter (Airy Technology, Orem, Utah). The Airy has a range of up to 4 million particles per cubic foot, logs data at 5 second intervals, and complies with the ISO 21501-4 standard for uncertainty and counting efficiency. All data were collected within 12 months of calibration, in accordance with manufacturer instructions.

In addition to the continuous instruments, ambient air was sampled over segments of 20-30 min through stainless steel adsorption/thermal desorption cartridges (Tenax TA plus Carbotrap 1TD) as in Pankow et al. *(18)*. Each cartridge was thermally desorbed and analyzed for VOCs using a gas chromatograph and mass spectrometer (see Pankow et al. *(19)*). 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 ng/l).

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 utilizing the formula:

$$C_{t,s} = \frac{TVOC_{t,s}}{\overline{TVOC}_s}\bar{C}_s$$

where $\bar{C}_s$ and $\overline{TVOC}_s$ are the average BTEX and TVOC concentrations on segment s, respectively. This approach uses the variability information in the TVOC data with the precision information available 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.

Air sample 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 PM inlet was at a height of 0.9 m. The CO diffusive sampler 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.

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.

2.2 Roadway data

GPS receivers recorded 1 Hz location data. Redundant GPS devices and on-bicycle video were used to cross-check the location data. Average daily traffic (ADT) estimates were available for street links in 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 arbitrary 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%.

In addition to the ADT GIS layer, two other GIS data sets were obtained for analysis: link-based transportation system plan (TSP) and bicycle network data. Both data sets were obtained from Metro (the metropolitan planning organization for Portland, Oregon), through the Regional Land Information System (RLIS).

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 valid GPS data points (longitude and latitude fields both present), 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 or inaccuracy in the GPS data. During 255 km of on-road sampling, 150 unique km of roadway were sampled. 60% of mixed-traffic links were sampled once; 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 resulting distribution of road type classifications for on-road observations was:

- Off-street path: 10,701 (10%),
- Bridge: 2,009 (2%),
- Local street: 49,560 (48%),
- Minor collector: 7,724 (7%),
- Major collector: 5,539 (5%),
- Minor arterial: 8,922 (9%),
- Major arterial: 16,866 (16%), and
- NA: 2,970 (3%).

The road type classifications and ADT for sampled links are mapped in Figure 1.

Real-time arterial traffic data at two control locations on a major arterial in the study area were obtained from the Portland Bureau of Transportation (PBOT). Ten-second vehicle counts (volume) 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 volume data. Lacking real-time traffic data for the entire network, the real-time traffic data from this facility was used to test for temporal traffic effects (beyond ADT).

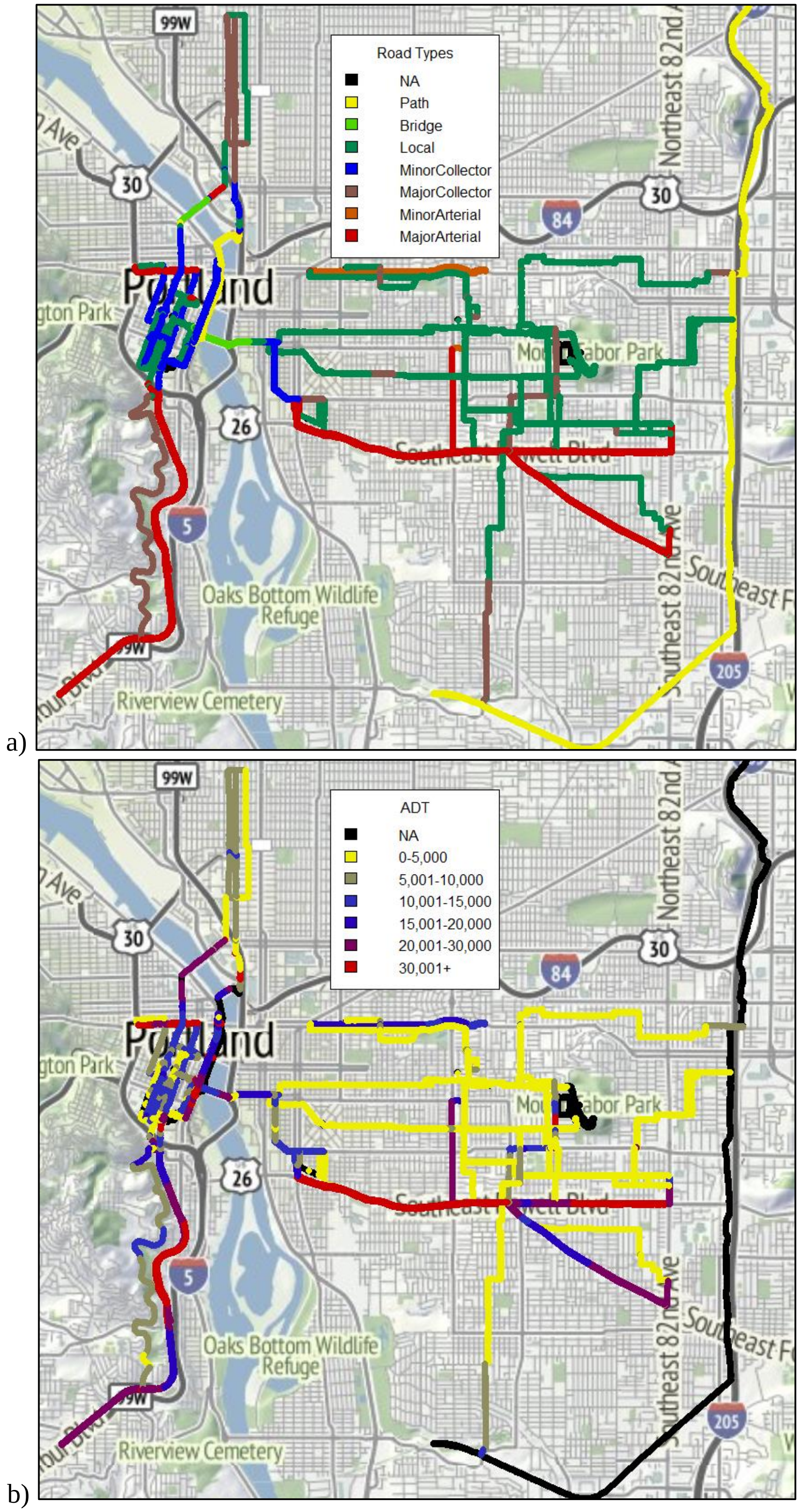

Figure 1. Associated road type classification (a) and ADT (b) on sampled roadways (background image from OpenStreetMap)

3 RESULTS

The average sampling conditions over 9 days were: temperature, 19 (11-25) °C; relative humidity, 75 (57-91) %; wind speed, 1.8 (0.6-3.6) mps. 5-second aggregation is used in modeling below to match the resolution of the PM device. At 5-second aggregation there were 14,301 observations with complete location and air quality data (20 hr).

Correlation coefficients among tested explanatory variables and BTEX concentrations are shown in Figure 2 using 5-second data. Traffic, ADT, and grade variables were set at 0 when sampling on an off-street path. |Grade| is the absolute value of the roadway grade in the direction of travel. LogAdt is the natural log-transformed ADT. StopEnRoute is a dummy variable for when the data collection bicycle was stopped during the course of a ride because of traffic signals, stop signs, traffic congestion, etc. (for up to 120 seconds). StartupEnRoute is a dummy variable for the first ten seconds after a StopEnRoute event. NearCrossing is a dummy variable for when the data collection bicycle was on a local road and within 25 m of a major road crossing. Crossing Proximity is the distance to a major road crossing. Traffic Speed, Traffic Volume, and Traffic Density are real-time traffic variables from the DWR sensors.

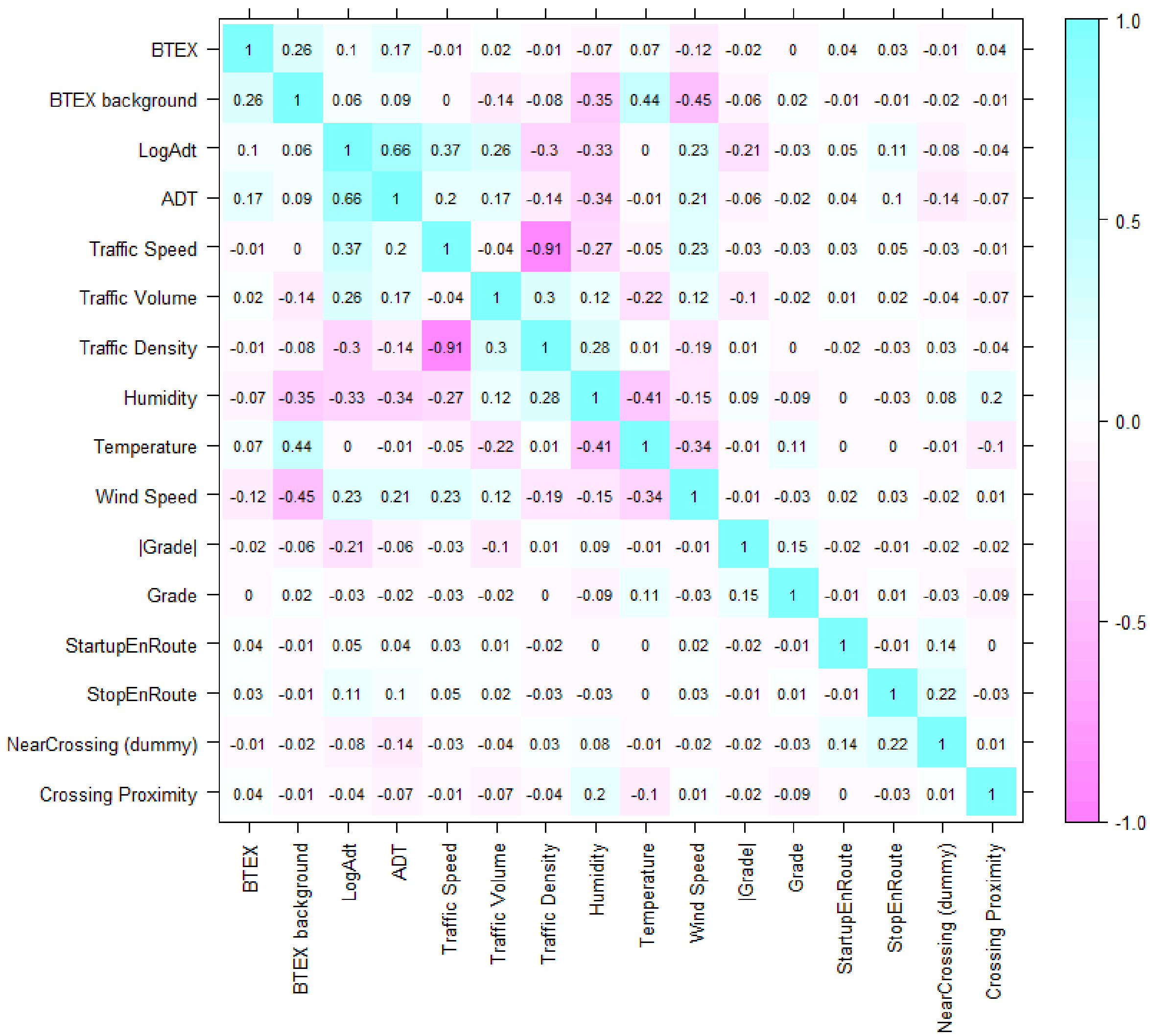

Figure 2 . Correlations among 5-second aggregated explanatory variables and BTEX exposure concentrations

Figure 2 shows that the real-time traffic variables are correlated amongst each other, as are weather variables. Background concentrations are positively correlated with temperature and negatively correlated with wind speed and humidity.

3.1 High-resolution model of BTEX exposure

A model of 5-second BTEX exposure concentrations was estimated using ordinary least squares with heteroscedasticity and autocorrelation consistent (HAC) standard errors. The statistical software R was used for analysis; HAC standard errors were estimated using the pre-whitened covariance matrix from Andrews and Monahan *(20)*. The measured explanatory variables in Figure 2 were tested by stepwise addition to the model. 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 (Figure 2), 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 joint consideration of lower Akaike Infomration Criterion (AIC), higher adjusted R^2, and inclusion of ADT in the set of significant explanatory variables. Alternative specifications (candidate final models) are discussed in the next section (3.2).

The preferred model is specified:

$$\ln(C_i^{ex}) = \beta_0 + \beta_1 \ln(\mathrm{C}_i^{bg}) + \beta_2 \mathrm{WindSpeed}_i + \beta_3 \mathrm{MixedTraffic}_i + \beta_4 \mathrm{Springwater}_i + \beta_5 \mathrm{I205Path}_i + \beta_6 \mathrm{ADT}_i + \beta_7 \mathrm{StopEnRoute}_i + \beta_8 S\mathrm{tartUpEnRoute}_i + \varepsilon_i$$

where ε_i is an error term and the other variables are defined in Table 1. The two path variables are for the main off-street facilities used in the data collection. The I-205 Path runs north-south parallel to a freeway with high ADT (100,000-150,000), intermittently inside and outside of an adjacent sound wall. The Springwater Path runs east-west between the river and the I-205 Path, including sections in parkland and sections parallel to a roadway in an industrial area.

Table 1. Variable definitions in high-resolution BTEX exposure model; i is the observation index

Variable	*Units*	*Description*
C_i^{ex}	ng/L	Measured exposure concentration
C_i^{bg}	ng/L	Measured concentration at the reference park location before the data collection which included observation i
$\mathrm{WindSpeed}_i$	mps	Scalar-average concurrent wind speed from the ODEQ station
$\mathrm{MixedTraffic}_i$	0,1	Dummy variable =1 if observation i is on a mixed-traffic (non-separated) travel way
$\mathrm{Springwater}_i$	0,1	Dummy variable =1 if observation i is on the Springwater off-street path
$\mathrm{I205Path}_i$	0,1	Dummy variable =1 if observation i is on the I-205 off-street path
ADT_i	1,000 veh/day	Average ADT estimate for the links traveled during observation interval i (if on a mixed-traffic facility, not an off-street path)
$\mathrm{StopEnRoute}_i$	0,1	Dummy variable =1 if observation i is during a stop while riding
$\mathrm{StartupEnRoute}_i$	0,1	Dummy variable =1 if observation i is within 10 seconds of a start while riding

The estimated model coefficients with HAC robust standard error estimates are shown in Table 2 (adjusted $R^2 = 0.318$). 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 0.853, and a Box-Ljung test is significant at $p < 0.01$. Regression of the squared residuals on an eight-factor RoadType variable rejects homoscedasticity by facility type (adjusted $R^2 = 0.020$ and $p < 0.01$).

Table 2 . High-resolution BTEX exposure model estimated coefficients

	Value	*Standard Error*	*t-statistic*	*p-value*
(Intercept)	0.595	0.221	2.695	0.007
$\ln(C^{bg})$	0.689	0.099	6.979	<0.001
WindSpeed	-0.137	0.025	-5.572	<0.001
MixedTraffic	0.353	0.060	5.883	<0.001
Springwater Path TRUE	1.038	0.433	2.395	0.017
I-205 Path TRUE	0.421	0.084	5.022	<0.001
ADT	0.014	0.001	9.153	<0.001
StopEnRoute TRUE	0.214	0.043	4.954	<0.001
StartupEnRoute TRUE	0.268	0.045	5.925	<0.001

Summary data on measured concentrations and the explanatory variables in the preferred model are shown in Table 3.

Table 3. Characterization of pollutant concentrations and explanatory variables

	minimum	*median*	*mean*	*maximum*
BTEX (ng/l)	0.01	6.28	9.83	1,020.00
CO (ppm)	0.00	0.56	0.59	10.72
$PM_{2.5}$ (pt/cc)	0.01	0.14	0.16	9.04
Wind speed (mps)	0.18	1.74	1.85	4.11
ADT (all links)	0	890	8,360	53,950
ADT (mixed-traffic facilities only)	116	3,626	10,600	53,950
Mixed traffic		68% TRUE		
I205 Path		6% TRUE		
Springwater Path		2% TRUE		
Stopped en route		9% TRUE		
Startup en route		4% TRUE		

The high-resolution exposure model coefficients in Table 2 show that background concentrations, wind, and roadway variables are important determinants of on-road exposure. The elasticity of on-road to background concentrations was 0.69. The ADT coefficient indicates that BTEX exposure is expected to increase by 1.4% for each additional 1,000 vehicles/day.

An established estimator for the effects of dummy variables on the dependent variable in a semi-log model is $\left[\exp\left(\beta - \frac{1}{2}SE_\beta^2\right) - 1\right]100\%$, where β is the estimated dummy variable coefficient and SE_β is its standard error *(21)*. The dummy variable coefficients can be interpreted as an expected BTEX concentration increase (compared to the reference park location) of:

- 42% on mixed-traffic roadways (in addition to ADT effects),
- 157% on the Springwater Path,
- 52 % on the I-205 Path,
- 24% while stopped during a ride, and
- 31% in the first 10 seconds of riding after a stop.

The difference in coefficients between the Springwater and I-205 paths is large. Inspection of the spatially-explicit data along the Springwater Path showed that VOC concentrations were high coincident with near-path industrial land use. Likely VOC-emitting businesses in the corridor include metal casting and machining, engine services, paint and power-coating, and other manufacturing. This finding emphasizes the important role of near-road, non-traffic sources of certain pollutants.

Table 4 shows the changes in sum of squared residuals (SSR) with the single-term deletion of model variables. Background concentrations are the strongest single explanatory variable in terms of explained variance, followed by ADT, facility classifications, and wind speed. Background concentrations and wind speed have similar combined SSR changes to the combined roadway/travel variables.

Table 4. Change in SSR with single-term deletion of explanatory variables

Dropped Term	*SSR*	*SSR change*
-	6888.70	-
$\ln(C^{bg})$	7746.70	858.04
WindSpeed	7034.00	145.35
MixedTraffic	7140.90	252.22
Springwater Path TRUE	7166.70	278.03
I-205 Path TRUE	7003.20	114.52
ADT	7290.50	401.79
StopEnRoute TRUE	6939.90	51.17
StartupEnRoute TRUE	6926.00	37.36

3.2 Alternative specifications

An alternative specification of the BTEX model that applies a natural log transformation to ADT has similar statistical fit: $R^2 = 0.32$ and the change in SSR associated with the $\ln(ADT)$ term is 461. The coefficient on the $\ln(ADT)$ term in that model is 0.126 ($p < 0.01$). The coefficient on the MixedTraffic dummy variable (which acts as an intercept for the $\ln(ADT)$ term) is -0.525 ($p < 0.01$); all other coefficients are nearly the same as the preferred model and significant at $p < 0.05$. The estimated $\ln(ADT)$ coefficient indicates BTEX exposure elasticity to ADT of 0.126, which aligns with the semi-elasticity in the preferred model (1.4% per 1,000 ADT) at an ADT of 9,000 – which would be expected on a mid-sized collector roadway and is very near the mean in Table 3. The non-transformed ADT specification was selected for the preferred model because the estimated coefficient on ADT was more consistent with changing specifications than in the $\ln(ADT)$ model.

Another alternative specification was created by replacing the ADT variable and the three facility dummy variables with an eight-factor RoadType variable (Park, I-205 Path, Springwater Path, Local Road, Minor Collector, Major Collector, Minor Arterial, Major Arterial). The R^2 of the model increased slightly to 0.33 and the RoadType factor was significant based on an F-test ($p < 0.01$). The ADT specification was selected for the preferred model because the ADT parameter would be easier to implement for non-measured facilities than an imprecisely classified factor variable.

A similar specification was tested adding 26 dummy variables for each individual roadway name (an attribute from the TSP GIS layer) with at least 2 minutes of on-road data. The overall model fit increased only slightly (adjusted $R^2 = 0.35$). Interestingly, the ADT coefficient is almost unchanged in this model (0.016) and still highly significant (suggesting that the ADT finding is robust to local variation in land-use and near-road point sources). Other than the I-205 and Springwater Paths, seven of the roadway name variables are significant at $p < 0.05$ based on HAC standard errors – all with positive coefficients. However, the MixedTraffic dummy variable coefficient is no longer significant. The road names with positive coefficients in this model are higher than expected from traffic and weather conditions, possibly due to near-road land uses (e.g. Springwater Path) or incorrect or outdated ADT estimates.

If background concentrations are not available, then the weather factors become more important variables. Removing the $\ln(C_i^{bg})$ term, the model R^2 falls to 0.23. Removing the $\ln(C_i^{bg})$ term but adding temperature and relative humidity terms brings the R^2 back up to 0.26. The estimated coefficient on the temperature term (in °C) is 0.046 ($p < 0.01$) and on the relative humidity term (in %) is -0.002 (not significant, with $p = 0.46$). The wind speed coefficient increases in magnitude to -0.253 and the other coefficients are largely unaffected. Both temperature and humidity were tested and found to be not significant at $p < 0.05$ with background concentrations included in the model.

The known effect of grade on motor vehicle emissions rates did not lead to a significant grade variable in the model. Proximity to a major roadway was not significant in the model when StopEnRoute and StartupEnRoute were included. Although static facility-related variables (ADT, facility dummy) were strong determinants of exposure, the dynamic traffic variables tested were not significant. This effect could be due to correlation between traffic conditions and meteorology/wind speed (Figure 2) or to the dominance of spatial over temporal traffic variables (especially for consistent times of the day). In other words, the variation in bicyclist exposure concentrations at one location is smaller than the variation over the course of a ride, as bicyclists traverse facilities of varying size and characteristics.

3.3 Comparing pollutants

A single model specification was estimated for all measured pollutants in order to compare the coefficients. The model was similar to the one specified in the previous section, but replacing background concentrations with temperature in °C (because background concentration data was not available for all pollutants). The model specification was

$$\ln(C_i^{ex}) = \beta_0 + \beta_1 \text{Temperature}_i + \beta_2 \text{WindSpeed}_i + \beta_3 \text{MixedTraffic}_i + \beta_4 \text{Springwater}_i + \beta_5 \text{I205Path}_i + \beta_6 \text{ADT}_i + \beta_7 \text{StopEnRoute}_i + \beta_8 S\text{tartUpEnRoute}_i + \varepsilon_i$$

The estimated model coefficients for natural log-transformed BTEX, TVOC, CO, and $PM_{2.5}$ concentrations are shown in Table 5. Coefficients with $p < 0.05$ are highlighted with bold text. The model was estimated using OLS with five-second aggregated data and HAC robust standard error estimates

Table 5. Comparison of high-resolution concentration model coefficients among pollutants (all dependent variables transformed by the natural log)

	BTEX		TVOC		CO		$PM_{2.5}$	
	Est.	p-val	Est.	p-val	Est.	p-val	Est.	p-val
(Intercept)	**1.000**	<0.001	**2.763**	<0.001	**1.224**	<0.001	**-1.173**	<0.001
Temperature	**0.049**	<0.001	**-0.055**	<0.001	**-0.137**	<0.001	**-0.021**	<0.001
WindSpeed	**-0.249**	<0.001	**-0.066**	0.002	-0.022	0.657	**-0.138**	<0.001
MixedTraffic	**0.348**	<0.001	**0.122**	0.043	**0.193**	0.044	**-0.282**	<0.001
Springwater Path	**1.175**	0.005	**1.179**	0.008	0.509	0.156	**0.242**	0.008
I-205 Path	**0.288**	<0.001	0.052	0.536	**0.657**	<0.001	**-0.366**	<0.001
ADT	**0.015**	<0.001	**0.017**	<0.001	**0.017**	<0.001	**0.003**	0.002
StopEnRoute	**0.204**	<0.001	**0.132**	0.004	-0.061	0.438	**0.316**	<0.001
StartupEnRoute	**0.264**	<0.001	**0.239**	<0.001	-0.013	0.858	**0.061**	0.036
N	13,946		13,946		10,756		13,707	
Adjusted R^2	0.257		0.165		0.155		0.140	

Comparison of roadway-related coefficients for the five pollutants Table 5 supports the expectation that CO and VOC are more strongly traffic-related than $PM_{2.5}$. The ADT coefficients in Table 5 are remarkably similar for BTEX, TVOC, and CO, and the MixedTraffic coefficients are similar as well. The CO concentrations on the Springwater Path are not nearly as elevated as for TVOC and BTEX, presumably due to near-road industrial sources which generate proportionally less CO than motor vehicles, with respect to VOC. The detailed location variables StopEnRoute and StartupEnRoute are not significant for CO.

The ADT coefficient is positive and significant for $PM_{2.5}$ but the MixedTraffic dummy variable is significant and negative. The negative MixedTraffic coefficient would be offset by the positive ADT coefficient for $PM_{2.5}$ exposure on larger mixed-traffic facilities. Negative MixedTraffic and I-205 Path coefficients for $PM_{2.5}$ suggest that the $PM_{2.5}$ concentrations at the park location were relatively high. Kaur and Nieuwenhuijsen *(9)* also found more significant associations with traffic for CO than $PM_{2.5}$.

3.4 Parallel path effects

In order to test the effects of minor detours on exposure, concentrations on four sets of paired parallel facilities were directly compared. The four comparisons in this section show that even minor, 1-2 block detours to parallel low-volume streets can significantly reduce exposure concentrations. Representative images for all four pairs of facilities are shown in Figure 3 (screen shots from on-bicycle video data).

E Burnside St. and SE Ankeney St. are parallel facilities separated by one block (80 m) with average ADT on the sampled links of 16,518 and 722, respectively. Burnside is classified as a District Collector in the TSP; Ankeney is classified as a Local Service Traffic Street. The facilities were ridden four times each over a distance of 2.8 km on two different days during the morning peak period. Concentrations of BTEX compounds were on average 44-88% higher on Burnside than Ankeney, 59% higher for total BTEX concentration. Other concentrations were 51% (TVOC), 201% (CO), and 9% ($PM_{2.5}$) higher on Burnside than Ankeney. All differences were significant based on a Wilcoxon rank sum test ($p < 0.01$).

N Williams Ave. and NE Rodney Ave. are parallel facilities separated by two blocks (160 m) with average ADT on the sampled links of 7,358 and 655, respectively. Williams is classified as a Neighborhood Collector in the TSP; Rodney is classified as a Local Service Traffic Street. The facilities were ridden three times. Concentrations were on average 329% (TVOC) and 221% (CO) higher on Williams than Rodney ($PM_{2.5}$ data were missing from these time periods). The differences were significant based on a Wilcoxon rank sum test ($p < 0.01$). Video data from Williams reveal frequent interactions (“leapfrogging”) with buses during the data collection period. In addition, Williams has undergone recent development and traffic volumes could be higher than reported in the ADT data.

Naito Pkwy is classified as a Traffic Access Street in the TSP, with average ADT on the sampled links of 19,092. A riverside path in Tom McCall Waterfront Park runs parallel to Naito Pkwy for 2 km, separated by 70 m. The segments were ridden four times. Concentrations were on average 112% (TVOC), 30% (CO), and 4% ($PM_{2.5}$) higher on Naito than the riverside path. The differences were significant based on a Wilcoxon rank sum test ($p < 0.01$) for TVOC and CO, but not $PM_{2.5}$ ($p = 0.06$). Unlike the previous comparisons of facilities separated by buildings, the parallel path has only sparse trees (see Figure 3) as a barrier to the emissions from vehicles on Naito. However, being immediately adjacent to the river, the dispersion characteristics are good.

Measurements were taken along a cycle track on SW Broadway between SW Clay St. and SW Jackson St. The seven-block segment (560 m) was ridden eight times total: two times each in the cycle track and in the far right traffic lane. Average TVOC concentrations were 9.2% higher on-road than in the cycle track, though the difference was not significant based on a Wilcoxon rank sum test ($p = 0.16$). Video data from Broadway showed that vehicle volumes were light during the data collection periods. For comparison, a 2011 study of UFP on the same cycle track measured 8-38% higher concentrations on-road than in the cycle track based on 6 sampling periods over 8 months of 2-7 hours each *(3)*. These results suggest that cycle tracks are useful to reduce bicyclist exposure concentrations by increasing the separation between bicyclists and motorized traffic, but that cycle tracks are not as effective as parallel paths.

Figure 3. Parallel facility comparisons (images from on-bicycle video data)

4 CONCLUSIONS

This paper provides the first mutli-pollutant quantification of the relationship between bicyclist exposure and ADT on a roadway. Semi-elasticity of BTEX, TVOC, and CO exposure to ADT was around 2% per 1,000 ADT, robust to several different specifications. These quantitative estimates of the impact of ADT on exposure concentrations provide a ready tool for analysts to calculate expected differences in exposure levels among routes. BTEX exposure on mixed-traffic facilities increased by 20-30% during stop-and-go riding, showing that detailed travel attributes can be important determinants of exposure, in addition to link-level characteristics. BTEX exposure on off-street facilities varied widely, from similar concentrations to the lowest-traffic local streets to similar concentrations to the highest-traffic arterials.

High exposure on off-street facilities was coincident with near-path industrial land use. In both ADT and parallel facility effects, $PM_{2.5}$ concentrations were much less impacted by traffic volumes than concentrations of CO and VOC.

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 control for diurnal variability, but were not jointly significant with weather and ADT variables in the model. Although more precise traffic data can improve the precision of the exposure models, ADT was of primary interest as the most widely-available roadway descriptor. Another limitation is the temporal sampling coverage; longitudinal studies using stationary monitors could be used to extrapolate these findings. Lastly, only near-road and weather variables were included in the models: land-use regression is left for future work. However, as noted in Section 3.2, the estimated effect of ADT on exposure appears to be robust to local variation in land-use and near-road point sources.

The results in this paper have clear policy and design implications. Roadway characteristics have a strong impact on bicyclists' exposure concentrations, and ADT seems to be a parsimonious approach to characterize the impact of mixed-traffic facilities on bicyclists' exposure. Direct comparisons of exposure concentrations on parallel routes showed that minor detours to nearby low-traffic facilities can dramatically reduce exposure concentrations; hence provision and usage of low-traffic parallel paths in residential areas is an effective way to reduce bicyclists' exposure. However, bicyclists traveling on off-street paths near industrial areas can have VOC exposure concentrations higher than most mixed-traffic facilities. Distance to traffic is a necessary but not sufficient condition to reduce exposure to BTEX compounds.

5 ACKNOWLEDGMENT

This research was supported by the National Institute for Transportation and Communities (NITC), Portland Metro, and the City of Portland. Alexander Bigazzi is supported by fellowships from the U.S. National Science Foundation (Grant No. DGE-1057604) and NITC.

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