Quantification and Modeling of Black Carbon Exposure for Seattle Commuters

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A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2017

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Program Authorized to Offer Degree:

School of Public Health

Environmental & Occupational Health Sciences

University of Washington

Abstract

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Background: Exposure to traffic-related air pollution may be elevated during commute trips, but could vary with different transportation microenvironments and commuting behavior. Given the variety of commute options available within urban settings, understanding the potential differences in exposures for different commuter choices has potential implications for health, and may inform individual commuter choices and transportation strategies to reduce exposures.

Methods: Black carbon concentrations, a surrogate for traffic-related air pollution, were measured for a stratified selection of commute trips for different transportation modes and for arterial and local roadways in Seattle, WA. Black carbon concentrations were analyzed to develop an exposure model capable of providing an estimate of commute exposure with respect to route characterization, mode of transportation, time of day, and ambient pollution level.

Results: Results generated typical black carbon exposures of commuters in the Seattle area differentiated by variables such as commute time, mode, and route. Sampling data was used to generate three exposure models utilizing these variables to predict an average black carbon exposure concentration based on commute characteristics. Regression model predictions of black carbon exposure significantly differed between transit modes; of all modes included in the models, transit tunnel predictions were highest and walking predictions were lowest. Within-mode comparisons indicate BC exposure predictions for arterial routes are higher than predictions for local/residential routes, are higher between the hours of 6-9 am than between the hours of 4-6 pm, and increase with increased ambient $PM_{2.5}$ levels.

Conclusion: Commute mode and route can impact personal exposure to black carbon. Better understanding of exposure differences for commute modes and routes in Seattle could enable commuters the opportunity to alter commute choices to minimize exposure to black carbon, as well as enable cities and municipalities such as Seattle to consider exposure potential when making decisions about public transportation infrastructure, such as bus type, placement of bus stops, or ventilation in transit tunnels.

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Acknowledgments

Thank you to my advisor, Dr. Edmund Seto, for his invaluable guidance and mentorship throughout this endeavor. Thank you to my committee members, Dr. Mike Yost and Dr. Chris Simpson, for their expertise and support. Thank you to my colleagues and friends at University of Washington for enriching my academic experience.

Introduction

Commuting in Seattle

It is estimated that workers in the United States spend the equivalent of 1.2 years of their lifetime commuting (McKenzie & Rapino, 2011).While exposures during commuting are not traditionally thought of an occupational health and safety issue as individuals are not exposed in the workplace, impacts of pollution exposures during commuting affect an enormous segment of workers. In Seattle alone, of 407,361 workers identified in the American Community survey, 93.2% report some form of commute to work. Of those commuters, the three most common modes of transportation are driving a personal vehicle (55.9%), using public transportation (21.0%, excluding taxicabs), and walking (10.7%), with an average commute time to and from work is approximately 55 minutes per day (United States Census Bureau., 2015). Previous studies indicate that while commute time constitutes a smaller proportion of each day, typically between 4-6%, commuting commonly accounts for upward of 20-30% of exposure to black carbon, a common surrogate for traffic-related air pollution (Dons, Int Panis, Van Poppel, Theunis, & Wets, 2012).

Increasingly, due to concerns about urban and regional traffic congestion, land use constraints, and environmental impacts, a variety of forms of public transportation options are available. Public transit in Seattle is robust and well-utilized. Public transit options in Seattle include bus service, ridesharing, rail travel, and water taxi. King County Metro, the public transit authority in Seattle, is the 8th largest bus agency in the United States, with daily ridership in 2015 averaging 400,000 on weekdays (American Public Transportation Association, 2015), and the bus fleet operated by King County Metro is the 5th largest in the nation with over 1,900 buses (Roman, 2016). Among buses within Seattle, there are a variety of types of buses, including traditional diesel engine buses, hybrid diesel-electric buses, bus rapid transit, and buses that run above or below ground (i.e., in the downtown tunnel in Seattle). Even for car commuting, increasingly there are alternatives to traditional fossil fuel engine vehicles, including hybrid and fully electric vehicles.

Existing Commuter Air Pollution Exposure Studies

Many studies have been conducted in locations around the world attempting to quantify traffic-related air pollution exposure, however, only a subset have explored differences in commuter exposure to traffic-related air pollution based on transportation microenvironments, primarily varying transportation modes and routes. Previous studies comparing black carbon and $PM_{2.5}$ concentrations between transportation modes have generally found higher concentrations when commuting by bus and car than commuting on foot or bicycle (de Nazelle et al., 2012; Dons et al., 2012; Kingham, Longley, Salmond, Pattinson, & Shrestha, 2013; Li et al., 2015). A subset of studies have assessed exposures based on fuel differences within-mode; Zuurbier et al., 2010 found higher pollutant concentrations in diesel buses compared to electric buses.

Health Effects of Traffic-Related Air Pollution

Traffic-related air pollution has been highly associated with an increased risk for a host of acute and chronic health effects in epidemiological and toxicological studies. Both short term and long term exposure to traffic-related air pollution, specifically fine particulate matter of which black carbon is considered a component. Cardiovascular and respiratory diseases are well-recognized health endpoints associated with long-term exposure to traffic-related air pollutants leading to premature mortality. (Collart, Coppieters, Mercier, Dramaix, & Levêque, 2015; Kampa & Castanas, 2008; Samet et al., 2000) . Short term exposure to traffic-related air pollutants has been associated with exacerbation asthmatic and allergic symptoms(Chow et al., 2006; Fang et al., 2012).

Black Carbon

Black carbon is a component of particulate matter (PM) formed from the incomplete combustion of fossil fuels, biofuels, and biomass (United States Environmental Protection Agency, 2015).. Currently, it is estimated that just over half of black carbon emissions in the United States come from transportation sources, with other major sources including industrial operations and open biomass burning (Lee et al., 2013) .Black carbon has often been used as a surrogate measurement for traffic-related pollution (Suglia, Gryparis, Schwartz, & Wright, 2008). Black carbon is an ideal surrogate measurement for traffic-related pollution in locations such as Seattle as traffic is a primary source and it can be measured effectively at low concentrations, as opposed to geographic areas with large amounts of open biomass burning. A recent systematic review from the World Health Organization indicated that black carbon may not be toxic in and of itself as an element of PM, but may be a “universal carrier” of chemicals to the human body via inhalation (Janssen et al., 2011).

Specific Aims

Exposure to air pollution during daily commuting can contribute to negative respiratory and cardiovascular health effects. An enhanced understanding of how commuting options affect air pollution exposures could help commuters plan their trip, if they so choose, to reduce exposure to black carbon and other traffic-related air pollutants. The purpose of this study is to explore how transportation mode and transit route is associated with black carbon exposure during commutes within Seattle and to develop an exposure model for Seattle commuters to predict exposure to black carbon based on commute microenvironments and other characteristics. The specific aims are:

Aim 1: Quantify typical black carbon concentration levels for a variety of commuting scenarios within the Seattle area.

The goal of specific aim (1) is to collect black carbon concentrations representative of exposures experienced by commuters within the Seattle area that can be utilized to develop an exposure model. This will involve collecting representative samples of black carbon concentrations for a variety of scenarios: on major and minor roadways, and for a variety of transportation modes utilized by commuters in the Seattle area. Sampling data will be analyzed to assess differences in the distributions of black carbon concentrations between scenarios.

Aim 2: Develop a commuter exposure model to estimate black carbon exposure based on different commute variables. It is hypothesized that route type, transportation mode, and commute time are determinants of black carbon exposure.

The goal of specific aim (2) is to develop a commuter exposure model capable of estimating black carbon exposure and determine the association between different commute characteristics and variations in black carbon exposure. The development of this model has the potential to help identify commute characteristics that contribute substantially to exposure to black carbon.

Methods

Study Setting

A total of 90 sampling commute trips were completed between October 2016 and January 2017. Black carbon concentrations were collected for commute trips conducted in northwest Seattle. All sampling was confined between 46th Street and S. Atlantic St. north and south, respectively. Sampling was conducted on Bus Rapid Transit (BRT) hybrid diesel electric buses, electric buses, diesel buses, gas-powered passenger cars, and electric cars, as well as at city bus stops, transit tunnels, and on foot. Of all transportation modes sampled, BRT was least available, with only three routes within Seattle city limits, and thus the experimental location was restricted proximally to an existing BRT line. BRT lines have been installed in areas of high ridership during typical commute hours; all experimental sampling was conducted in Seattle districts in which BRT lines run. The experimental arterial road selected for the study was Highway 99 (Aurora Avenue), which is serviced by Bus Rapid Transit (RapidRide) “E line. Highway 99 averages a traffic flow exceeding 50,000 vehicles per day (Seattle Department of Transportation [SDOT] - Traffic Operations Division, 2015). Local roadways utilized in the study were classified as roadways not exceeding estimated traffic flows of 2,500 vehicles per day and at least 500 m from the major arterial roadways.

Air Pollution Data Collection

All black carbon sampling was conducted using a MicroAeth Black Carbon AE51 monitor (AethLabs, USA) between October 2016 and January 2017 during typical weekday rush hour intervals of 7-9 am and 4-6 pm. The instrument was transported in a backpack with the inlet at breathing zone height. The MicroAeth monitor was run at a 30-second time resolution as this is recommended for measurement of traffic and transportation impacts to optimize signal-to-noise ratio. Instrument flow rate was set at 100 ml/min to minimize effects of filter overloading or inadequate loading preventing detection. Sampling in each microenvironment was conducted in 15-minute intervals on weekdays during the aforementioned commute hours.

Detailed location information for each mode (and route when applicable) can be found in Appendix 1. All diesel bus, hybrid diesel-electric bus, bus rapid transit, arterial gas-powered car and arterial electric-powered car sampling followed an identical route; bus stop utilized for sampling were along the same route. The route utilized for electric bus sampling was distinct from the route for all other bus types in the study, but did include an overlapping portion. Because bus service is typically constrained to high traffic volume roadways, no data collected on buses, in transit tunnels, or at bus stops was classified as 'local' with respect to route classification.

Table 1. Scenarios sampled in study.

Mode	Route Classification	
	Arterial	Local
Bus Modes		
Bus Rapid Transit	X	
Hybrid Diesel Electric Bus	X	
Diesel Bus	X	
Electric Bus	X	
Personal Car Modes		
Electric Car	X	X
Gas Car	X	X
Pedestrian Activities		
At Bus Stop	X	
At Stop in Transit Tunnel	X	
Walking	X	X

Data Analysis

All data analysis was performed in RStudio Version 1.0.136 (RStudio Team, 2015) . Descriptive statistics were computed to provide a summary of commute data to understand mean, median, and standard deviation of black carbon concentrations for different transit modes and routes. Multiple linear regression was used to create an exposure model capable of estimating natural log-transformed black carbon mass concentration during a given commute based on the following variables:

1. Mode of transportation
    a. Bus Rapid Transit
    b. Hybrid diesel electric bus
    c. Electric bus
    d. Diesel bus
    e. Gas-powered passenger car

f. Electric car

g. Walking

h. Transit Tunnel

i. Bus Stop

2. Route Classification

a. Major Arterial

b. Local load

3. Time

a. 6-9 AM

b. 4-6 PM

4. Background $PM_{2.5}$ concentration

The covariate transportation mode includes both active and passive modes of transportation commonly utilized by commuters in Seattle, as well as bus stop and transit tunnel microenvironments, which although not traditionally thought of as transportation 'modes', may constitute considerable portions of commuting time and exposure for mass transit users. Mass transit modes included in the study included only buses.

While the model output provides only an estimation of black carbon mass for a commute with a solitary mode, route, and time combination, real-world commuting does not always prescribe to this. The following model can incorporate a commute with multiple modes, routes, and/or times to provide an estimation of a total commute black carbon mass:

$$BC = \sum_{n=1}^{n=i} C_n \cdot T_n \cdot IR_n$$

n = each leg of commute with unique transportation mode and route characteristics

C_n : average black carbon concentration of specific route and mode, in ng/m3

T_n : time

IR_n: inhalation rate, in m^3/min

Ambient $PM_{2.5}$ concentration was included in analysis to account for day to day variability by including ambient $PM_{2.5}$ measurements from a stationary monitor a few miles south of the sampling area, available from Puget Sound Clean Air Agency. A single hourly $PM_{2.5}$ mean concentration from the stationary monitor was included in all regression models for each experimental commute. While there is a stationary monitor closer to the sampling site, its proximity to a major junction of interstates caused concern for its use to capture variability in ambient air pollution and not variability due to traffic-related factors. A comparison of measurements from the two potential monitors and a map of their locations can be found in Appendix 2 and 3. However, when considering locations for air monitor installation found day-to day variability in $PM_{2.5}$ measurements was up to ten times greater than variability due to site location. (Goswami, Larson, Lumley, & Liu, 2002)

RESULTS

Aim 1: Quantification of typical black carbon exposure levels while commuting

The continuous variable measured in Aim 1 is black carbon (BC). BC concentrations were found to be lognormally distributed, as evidenced in Appendix 4. Tables 2 and 3 summarize the black carbon concentrations for different transportation modes. Analysis in Table 2 was conducted using all 30-second data points (300 per mode), and analysis in Table 3 was conducted using geometric means of each sampling period (10 per mode). Both methods suggest transit tunnels had higher mean and median BC concentrations compared to the remainder of the modes; sampling at bus stop locations and while walking produced the lowest mean and median black carbon concentrations.

Table 2. Summary statistics of black carbon concentrations by mode with 30-second time resolved data.

		BC (ng/m^3)			
Mode	**n**	**mean**	**SD**	**GM**	**median**
Gas Car	300	2119	683	1645	1789
Electric Car	300	951	664	979	918
Hybrid Diesel Electric Bus	300	3547	988	3119	2513
Electric Bus	300	1651	642	1315	1030
Diesel Bus	300	2079	518	1506	1627
Bus Rapid Transit	300	1884	739	1514	1460
Bus Stop	300	975	451	801	783
Tunnel	300	18281	3202	13447	12986
Walking	300	783	503	400	604

Table 3. Summary statistics of black carbon concentrations by mode with geometric means of 15-minute sampling periods.

		BC (ng/m^3)			
Mode	**n**	**mean**	**SD**	**GM**	**median**
Gas Car	10	2278	806	2082	2369
Electric Car	10	904	332	859	818
Hybrid Diesel Electric Bus	10	3649	2331	3096	2667
Electric Bus	10	1378	354	1337	1423
Diesel Bus	10				
Bus Rapid Transit	10	1953	800	1813	2058
Bus Stop	10	795	386	730	635
Tunnel	10	17502	6896	16123	15671
Walking	10	601	228	551	625

Table 4 provides descriptive statistics based on route classification based on commute geometric mean data. When comparing mean BC concentrations, differences between arterial and local routes were more pronounced when traveling in a gas passenger vehicle compared to an electric vehicle, or on foot; however, when comparing median concentrations, a similar degree of variation between morning and evening concentrations was observed for all three modes, as observed in Figure 1. Data for the remainder of the modes not included in this type were classified entirely as arterial, as public transit environments including buses, transit tunnels, and bus stops, are generally confined to heavily trafficked and accessible roadways.

Table 4. Summary Statistics for Transit Modes Stratified by Route Classification

		BC (ng/m³)			
Mode	**n**	**mean**	**SD**	**GM**	**median**
Gas Car					
Arterial	150	2491	1977	1747	2094
Local	150	1595	797	1306	1815
Electric Car					
Arterial	150	933	689	805	752
Local	150	729	456	603	529
Walking					
Arterial	150	645	683	418	524
Local	150	496	388	351	428

Table 5 provides descriptive statistics of black carbon concentrations for each mode stratified by route, utilizing the 30-second sampling data points. Morning commutes generally corresponded with higher black carbon when considering both mean and median values, although in a few instances for gas car and electric bus data evening concentrations were slightly higher. Figure 1 illustrates the distribution of sampling commute geometric means of each sampling period by mode and commute time. For all modes except gasoline-powered car, observed BC concentrations were higher in the morning hours of 6-9 am than the evening hours of 4-6 pm. When considering route and in addition to time of day (Figures 2 & 3), all modes had higher observed BC concentrations in the morning commute hours than in the evening commute hours.

Table 5. Summary Statistics for Transit Modes Stratified by Time of Day

		BC (ng/m^3)			
Mode	**n**	**mean**	**SD**	**GM**	**median**
Bus Rapid Transit					
AM	150	2431	1050	2094	2182
PM	150	1194	632	1042	1092
Bus Stop					
AM	150	1347	876	1134	1308
PM	150	655	387	545	628
Diesel Bus					
AM	150	2192	1237	1989	1882
PM	150	1746	1294	1262	1327
Electric Bus					
AM	150	1414	683	1238	1343
PM	150	1503	464	1418	1528
Electric Car					
AM	150	1187	755	948	1009
PM	150	860	603	710	760
Gas Car					
AM	150	2391	1960	1742	1920
PM	150	2230	1718	1567	1977
Hybrid Bus					
AM	150	4760	2857	4038	3936
PM	150	3091	2023	2635	2515
Transit Tunnel					
AM	150	23030	18444	18795	17073
PM	150	12619	9244	9020	12672
Walking					
AM	150	865	564	736	695
PM	150	496	388	351	428

Figure 1. Comparison of geometric means of sample commutes by mode and stratified by time of day.

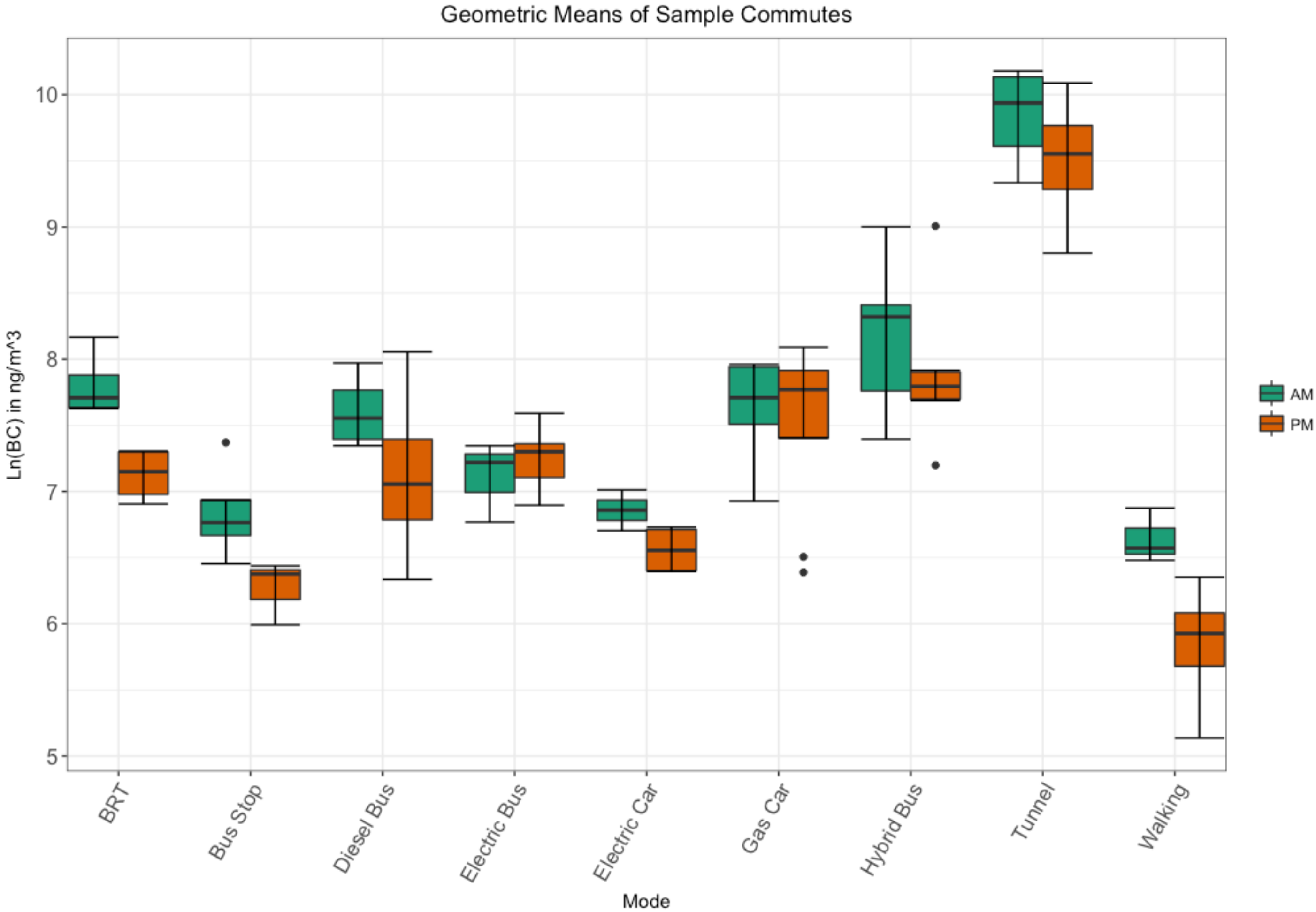


Figure 2. Comparison of morning BC exposure concentrations by route classification.

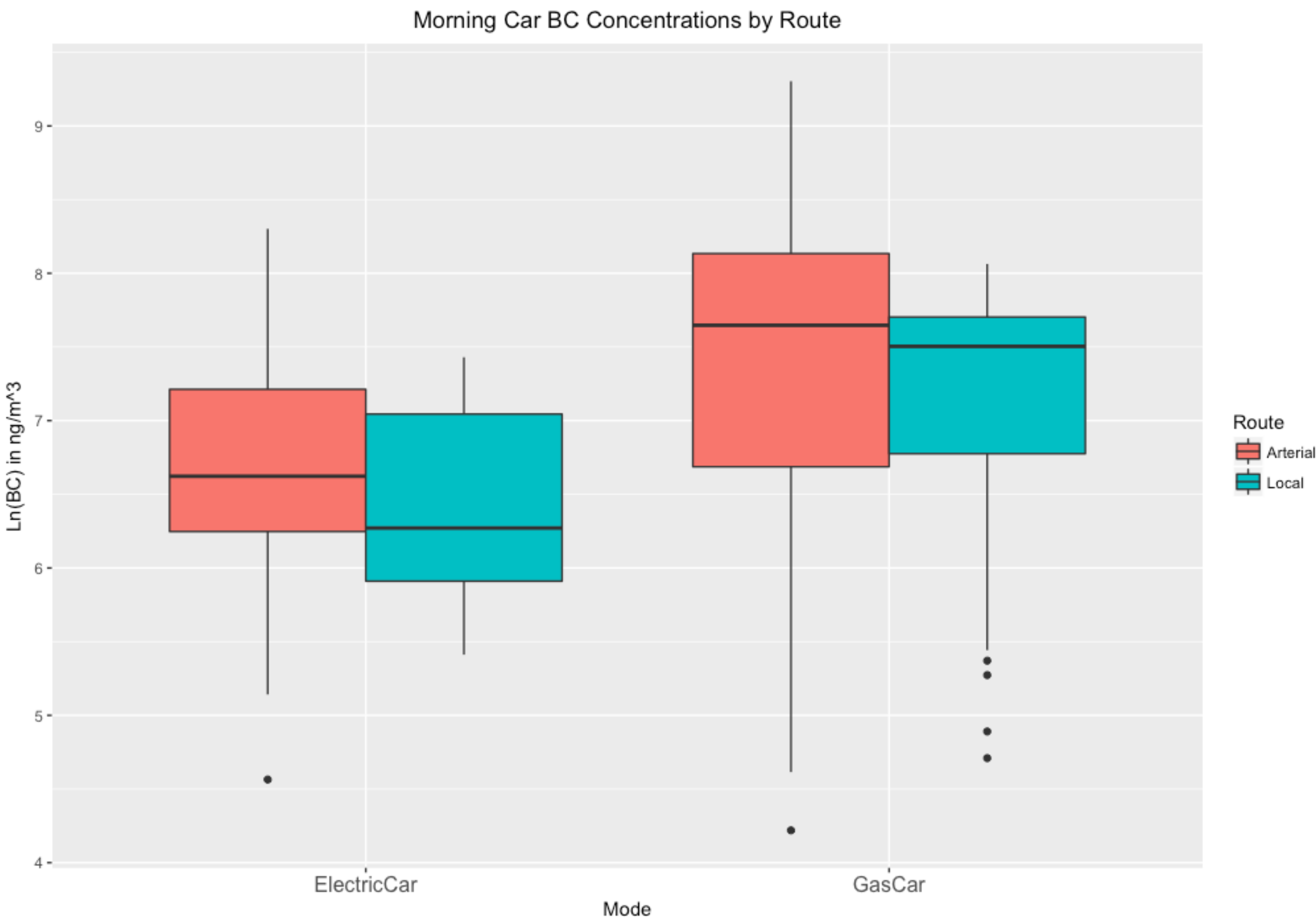
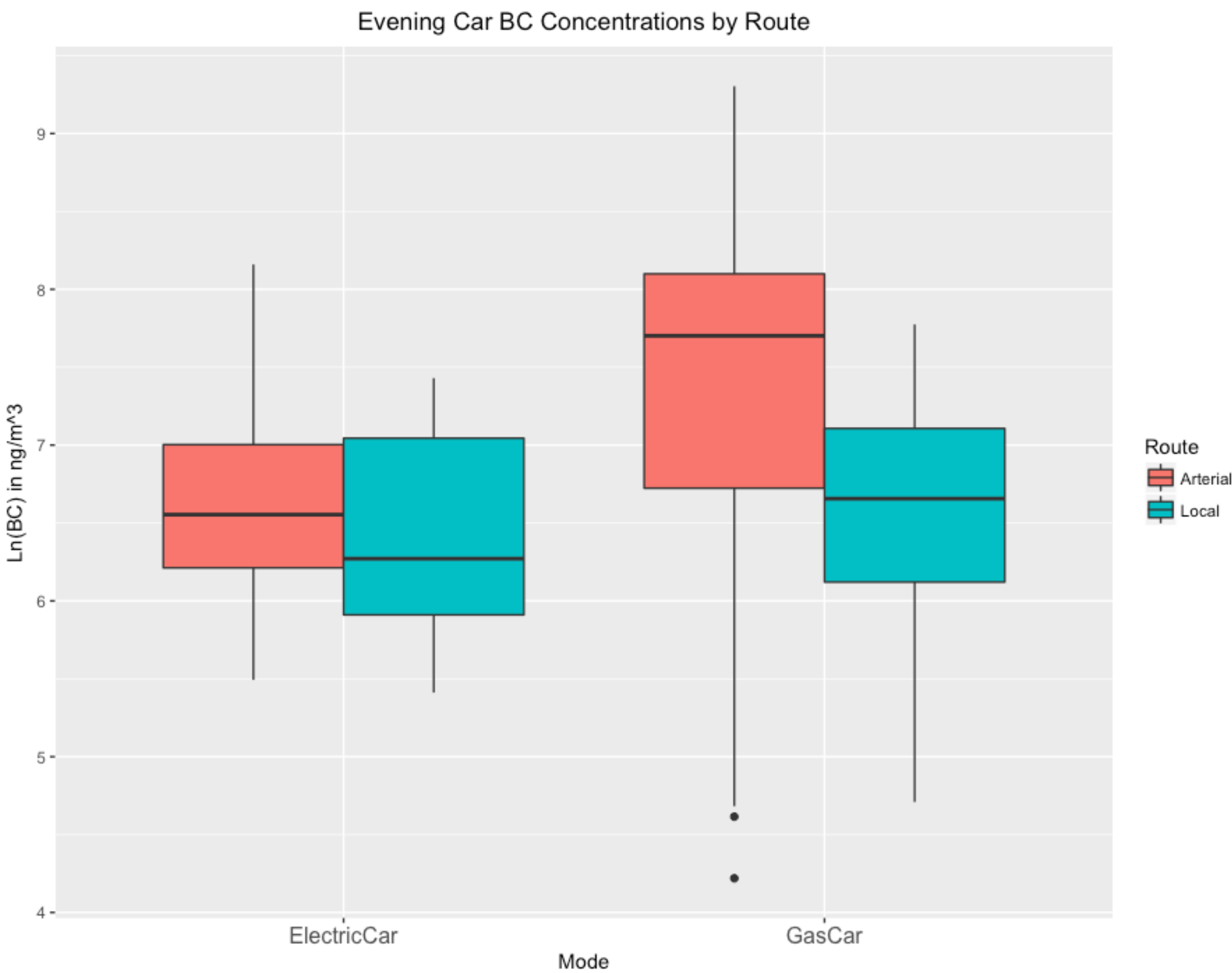


Figure 3. Comparison of evening BC exposure concentrations by route classification.



Aim 2: Commuter Exposure Models

Three regression models are presented for prediction of ln(BC). Table 6 outlines results of a multiple regression analysis with continuous 30-second ln(BC) as a continuous outcome and mode, route, commute time, and background as independent variables. In the model, the intercept represents ln(BC) for the reference case (i.e., BRT on an arterial during the AM commute time).

Table 6. Results of multiple regression analysis for ln(BC) with 30-second time resolved data

Parameter		Estimate	SE	95%Confidence Int. Lower	Upper	p-Value
Intercept		7.15	0.039	7.08	7.23	< 2e-16
Mode						
	Diesel Bus	0.80	0.047	-0.011	0.17	0.088
	Electric Bus	-0.22	0.050	-0.32	-0.13	< 2e-16
	Electric Car	-.044	0.057	-0.055	-0.33	1.47e-14
	Gas Car	0.028	0.044	-0.59	0.11	0.528547
	Hybrid Bus	0.75	0.04	0.69	0.84	< 2e-16
	Bus Stop	-0.51	0.054	-0.63	-0.41	< 2e-16
	Transit Tunnel	2.21	0.051	2.11	2.32	< 2e-16
	Walking	-1.06	0.06	-1.18	-0.93	< 2e-16
Route						
	Local	-0.16	0.047	-0.26	-0.07	0.00050
Commute Time						
	PM	-0.39	0.0029	-0.44	-0.34	< 2e-16
Background						
	Ambient $PM_{2.5}$	0.05	0.002	0.046	0.057	< 2e-16

Statistically significant increases in BC exposure were associated with hybrid bus and transit tunnel microenvironments, compared to statistically significant decreases in BC exposure associated with electric bus, electric car, bus stop, and walking microenvironments; BC exposures in diesel bus and gas passenger car microenvironments were not found to be significantly different from BRT. Route, time of day, and ambient $PM_{2.5}$ were all found to have statistically significant associations with BC exposure Consistent with patterns observed from descriptive statistics, black carbon exposure estimations from the model decrease with evening commutes and local routes, and lower ambient $PM_{2.5}$ concentrations correspond to lower BC exposure.

Table 7 outlines results of a multiple regression analysis with 15-minute geometric mean ln(BC) as a continuous outcome and mode, route, commute time, and background as independent variables. As opposed to regression output outlined in Table 6, electric bus as a mode and route are not statistically significant predictors of black carbon exposure when analyzing only sampling commute geometric means.

Table 7. Results of multiple regression analysis for ln(BC) geometric means of 15-minute sampling periods.

	Parameter	Estimate	SE	95% Confidence Int. Lower	Upper	p-Value
Intercept		7.43	0.17	7.09	7.77	< 2e-16
Mode						
	Diesel Bus	-0.10	0.21	-0.52	0.32	0.642570
	Electric Bus	-0.30	0.21	-0.72	0.12	0.156370
	Electric Car	-0.69	0.23	-1.15	-0.23	0.003822
	Gas Car	0.02	0.19	-0.36	0.41	0.897436
	Hybrid Bus	0.55	0.19	0.17	0.93	0.005159
	Bus Stop	-0.86	0.22	-1.30	-0.43	0.000203
	Transit Tunnel	2.2	0.20	1.80	2.61	< 2e-16
	Walking	-1.23	0.22	-1.66	-0.79	4.02e-07
Route						
	Local	-0.43	0.24	-0.93	0.057	0.081949
Commute Time						
	PM	-0.34	0.099	-0.53	-0.14	0.001118
Background						
	Ambient $PM_{2.5}$	0.033	0.011	0.010	0.055	0.004810

Table 8 presents results of a third regression model with outcome and predictor variables identical to the previous two models, but only including modes with differentiated route data; in all models, only the electric car, gas car, and walking modes had data collected on both arterial routes and local routes. As public transit in Seattle is generally confined to high-traffic roadways, no "local route" data was collected for any bus, transit tunnel, or bus stop sampling, and all corresponding data points were classified as arterial for route designation. In the previous model using sampling commute geometric mean data, the association between route and BC exposure was not found to be statistically significant. The regression model outlined in Table 8 indicates that when considering only modes with both local and arterial route samples, the association between route and BC exposure is statistically significant with lower BC exposure predications for local routes than arterial routes.

Table 8. Results of multiple regression analysis for ln(BC) geometric means of 15-minute sampling periods for modes with local and arterial route commutes.

				95% Confidence Int.		
	Parameter	Estimate	SE	Lower	Upper	p-Value
Intercept		6.88	0.21	6.43	7.32	< 2e-16
Mode						
	Gas Car	0.64	0.22	0.17	1.12	0.00931
	Walking	-0.19	0.30	-0.82	0.45	0.54070
Route						
	Local	-0.46	0.24	-0.85	-0.12	0.02652
Commute Time						
	PM	-0.55	0.18	-0.93	-0.18	0.00620
Background						
	Ambient $PM_{2.5}$	0.05	0.017	0.013	0.087	.00979

Discussion

This study evaluated exposure to black carbon. The results of this study indicate differing commuting transportation modes and routes influence BC exposure. Results from regression models indicate that mode, route, time of day, and background $PM_{2.5}$

Of all factors investigated in this study, transportation mode appears to be the strongest contributor to BC exposure during commute. Enclosed microenvironments, including passenger vehicles, buses, and transit tunnels, had higher overall BC levels than did open air microenvironments at bus stops and on foot. However, passenger vehicles and buses had substantial variation when considering fuel type. Sampling completed in an electric passenger vehicle had considerably lower levels of black carbon compared to a traditional gas powered vehicle. When accounting for ambient pollution level, commute time (AM vs PM), and route, the black carbon levels in the electric passenger vehicle were approximately half of black carbon levels measured in the gas-powered passenger vehicle. Similar variation occurred when evaluating exposure differences between buses with differing fuel types.

Consistent with other published studies, BC concentrations on buses using diesel fuel had markedly higher BC concentrations than purely electric-powered buses (Zuurbier et al., 2010). While diesel bus BC estimations were not statistically significant in either regression model, hybrid diesel electric buses had around 2.5 times higher exposures than measured on electric buses. However, it is noteworthy that while a portion of the experimental sampling route for electric buses did overlap with the experimental route used for all other bus types, the route were not identical as electric buses only travel on routes with established electric power lines. A map of experimental routes can be found in Appendix 1. Results indicate that when exploring black carbon exposures differences between transportation modes, looking at car versus bus concentrations alone may not be sufficient; fuel type may be an equally important variable to consider. Furthermore, variation in exposure levels between vehicles indicates self-pollution may be a considerable source of black carbon within a vehicle.

When comparing out-of-vehicle modes, transit tunnel as mode resulted in increased regression estimates of BC exposure, while walking and bus stop modes contributed to lower regression estimates of black carbon exposure. While previous studies have found that underground transit terminals have higher BC concentrations than buses (Yang et al., 2015), the elevated levels in the transit tunnels were somewhat unforeseen as city buses going through downtown transit tunnels in Seattle are required to run on electric power when in the tunnels. Our findings might indicate that hybrid diesel electric buses are still emitting exhaust when travelling through downtown transit tunnels. In all regression models, walking reduced exposure predictions the most out of all experimental modes, consistent with previous studies(Dons et al., 2012; Li et al., 2015)

Choice of route also significantly influenced black carbon exposures. As mentioned previously, only car and walking modes had data collected on routes classified as local, in addition to sampling conducted on arterial routes. When comparing within-mode, arterial routes had elevated levels of black carbon compared to local routes, with the regression model estimates indicating 37% lower average black carbon concentrations on the local experimental route compared to arterial routes. This finding is consistent with previous exposure studies (Dons et al., 2013; Hung et al., 2014), as well as studies utilizing stationary monitoring and land-use regression models (Padró-Martínez et al., 2012; Zhou & Levy, 2007)

Results from all regression models suggest black carbon exposures are significantly higher during morning commute hours than evening commute hours. This pattern is consistent with previous research exploring diurnal variation in particulate air pollution concentration; concentrations tend to peak during morning hours due to boundary layer, mixing, and temperature effects (Liu et al., 2015; Sahu, Kondo, Miyazaki, Pongkiatkul, & Kim Oanh, 2011; Yadav, 2014) . The typical hours during which peak particulate matter concentrations were observed in previous studies overlap with morning commute hours sampled in this study.

Results from all regression models also suggest a positive association between ambient $PM_{2.5}$ concentrations and black carbon exposures for commuters. Ambient $PM_{2.5}$ was used in this study in an attempt to capture day-to-day variability in air quality as a result of meteorological factors such as wind speed and direction, precipitation, relative humidity, and temperature, that were not otherwise controlled but which potentially influence pollutant concentrations. While there was a statistically significant association between ambient $PM_{2.5}$ concentration and black carbon exposures when commuting, it was substantially smaller than associations observed for mode, route, and time of day. As discussed in the methods section of this thesis, ambient $PM_{2.5}$ data was retrieved from a stationary monitor a few miles from the sampling area, and only provided an hourly average that in some cases varied substantially hour to hour. As experimental sampling periods were only 15 minutes in length, there is possibility of discrepancy between average hourly $PM_{2.5}$ data included in exposure modeling and actual $PM_{2.5}$ concentration during each specific sampling period, which could have led to either an over or underestimation of association, which could have been lessened with simultaneous $PM_{2.5}$ personal monitoring, or finer resolution ambient air quality data, neither of which were feasible in the context of this preliminary study.

The three black carbon exposure models largely exhibit agreement for directional influence of each covariate on overall BC exposure predictions, although there was some discrepancy in significance and magnitude of prediction of BC exposure. The regression model outlined in Table 7, which utilized geometric mean BC concentration of each experimental commute, had a higher intercept of 7.43 compared to the intercept of 7.15 from the regression model in Table 6, corresponding to black carbon exposure predictions of 1686 ng/m^3 BC and 1274 ng/m^3, respectively. Of the parameters that were statistically significant in both models, impact of commute time of day and ambient $PM_{2.5}$ concentrations were quite similar, while mode estimates varied to a greater extent. A more robust dataset of sampling commutes would be ideal to capture true differences in transport microenvironments.

Finally, it is worth noting the differentiation between exposure and dose, and subsequent implications for results of this study; of the two measures, dose is the most important to consider in relation to potentially harmful health effects. As the route of entry for black carbon is inhalation, inhalation rate is necessary to consider to determine black carbon dose when commuting. While this study did not attempt to integrate inhalation rate data, inhalation rates vary between different modes of transportation, especially when comparing active modes of transport such as walking or bicycling, to more passive modes such as sitting in a vehicle. For example, when comparing average inhalation rates for sitting, standing, and walking from the EPA Exposure Factors Handbook, walking is associated with the highest inhalation rates (inhalation rates vary by individual factors including gender, age, speed, etc). Even though the results of this study indicate exposure levels are lowest for walking among all other modes sampled, black carbon dose may be proportionally higher compared to exposure than for other modes due to inhalation rate. Even sitting and standing inhalation rates are discernably different, and as such, dose may vary within modes such as buses or bus stops based on whether an individual is sitting or standing.

Strengths

Few studies have sought to model personal exposure to black carbon based on commute characteristics in addition to quantifying exposure. This study demonstrated feasibility of creating a commuter exposure model based on personal exposure sampling, which could provide justification for conducting this nature of study on a larger level that could be used to develop trip-planning applications or other resources to help commuters understand and minimize exposure to black carbon and other traffic-related pollutants if they so choose.

This study is novel in exploring exposure differences between a gasoline-fueled passenger vehicle and a purely electric passenger vehicle. Current projections position electric vehicle sales to account for 35% of global annual vehicle sales by 2020 compared to 1% now (Bloomberg New Energy Finance, 2016) , and thus exposures differences between traditionally fueled vehicles and electric vehicles may be increasingly relevant in coming decades. Few studies have explored differences in exposure on buses aside from traditional diesel powered and electric powered buses.

Limitations

The study was conducted over a limited number of days during fall and winter, and results don't fully capture potential seasonal variability in black carbon concentrations in Seattle. Ideally, simultaneous inter-modal and inter-route sampling would have been conducted to eliminate day to day (and in some cases, hour to hour) background variability, including meteorological conditions and traffic volume. As this was not feasible, ambient $PM_{2.5}$ concentration from a stationary monitor miles from the sampling area was included in all regression models to capture account for variability, but this measure may not have accurately captured variability as a monitor closer to the sampling area. Due to instrument limitations, only one aethalometer was used during sampling; while the aethalometer utilized was properly calibrated, no assessment of instrumental agreement was conducted to assess repeatability. A small geographic area of Seattle was captured by experimental routes, and results may not be generalizable to greater Seattle or other metropolitan areas.

Conclusion

This was a small scale preliminary study assessing differences in black carbon exposure concentrations between commute modes and routes in Seattle. The results of this study indicate choice of commute mode and route can impact personal exposure to black carbon. An increased understanding of exposure differences for commute modes and routes in Seattle could afford commuters the opportunity to alter commute choices to minimize exposure to black carbon.

Future studies quantifying and modelling black carbon exposure based on commute characteristics such as transportation mode and route could potentially inform and influence commuting behavior on both an individual and collective level. An improved understanding of the relationship between commute characteristics and exposure to black carbon could enable commuters to achieve reduction in black carbon exposures if desired by selection of low exposure modes and routes, or by attempting to minimize time in high exposure microenvironments. On a larger scale, an improved understanding of the relationship between commute characteristics and exposure to black carbon could enable cities and municipalities such as Seattle to consider exposure potential when making decisions about public transportation infrastructure, such as bus type, placement of bus stops, or ventilation in transit tunnels.

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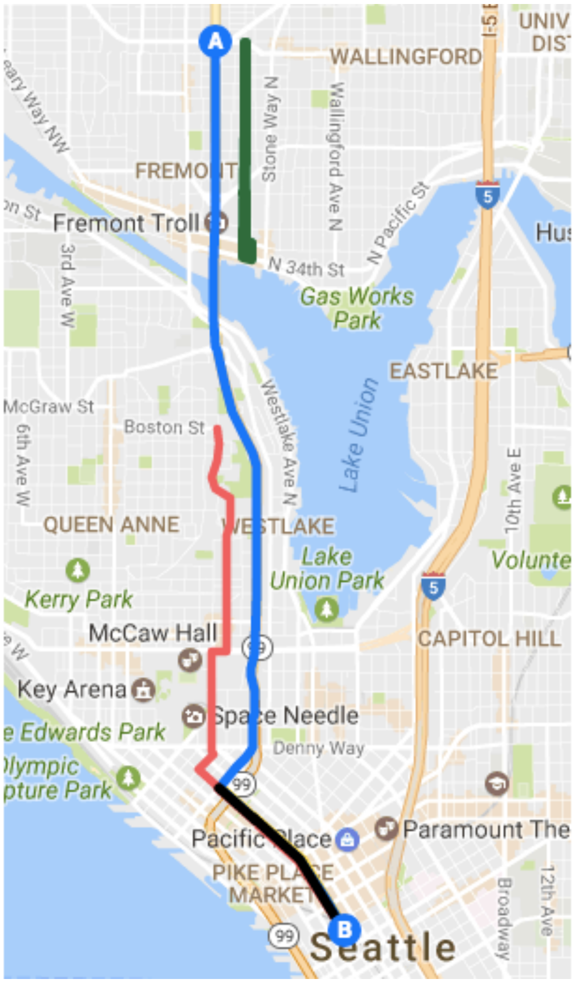
Appendices

Appendix I. Sampling Routes



Local Car Route and Local Walking Route

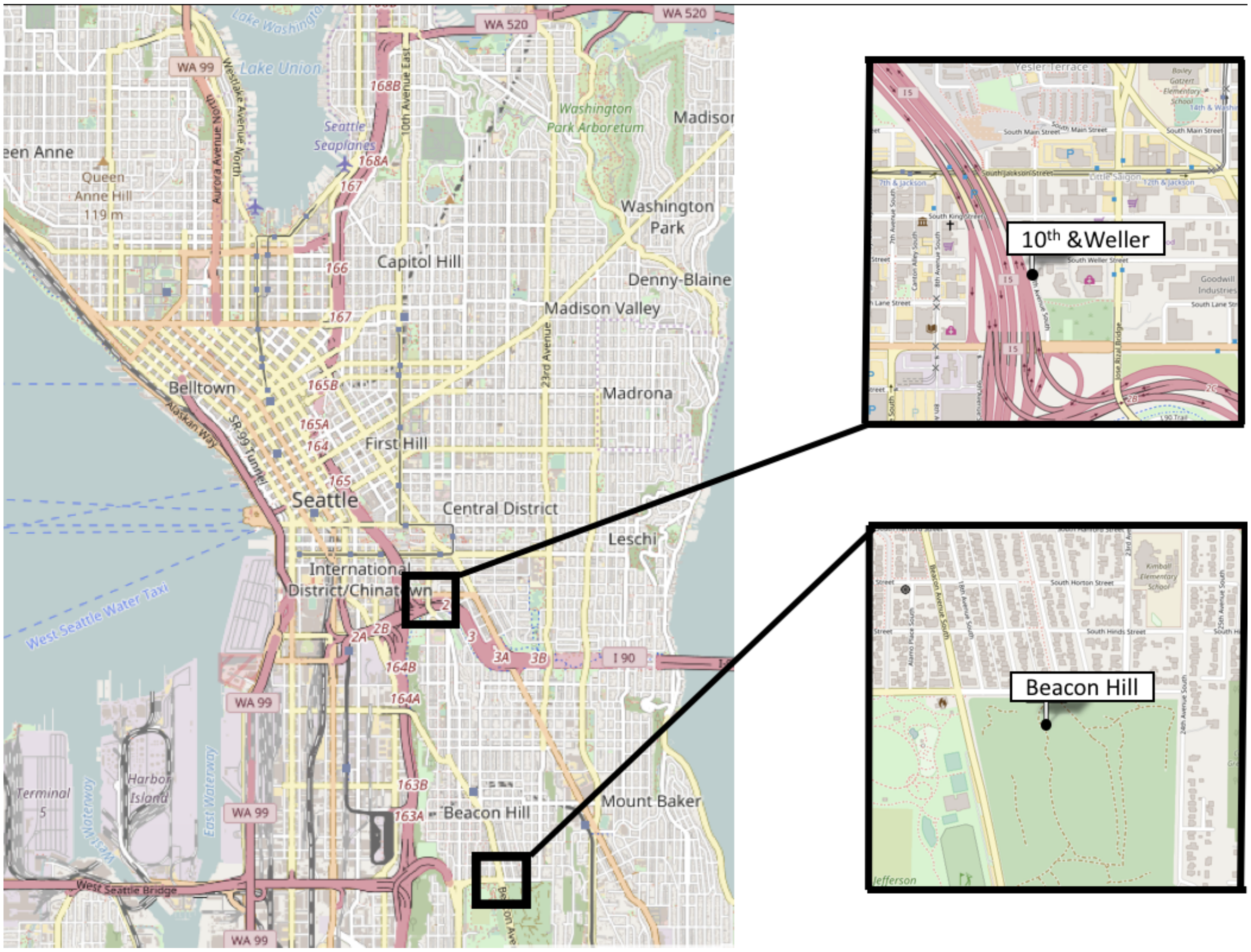
Electric Bus Route

BRT, Hybrid Diesel-Electric Bus, Diesel Bus, and Arterial Car Route

Arterial Walking Route

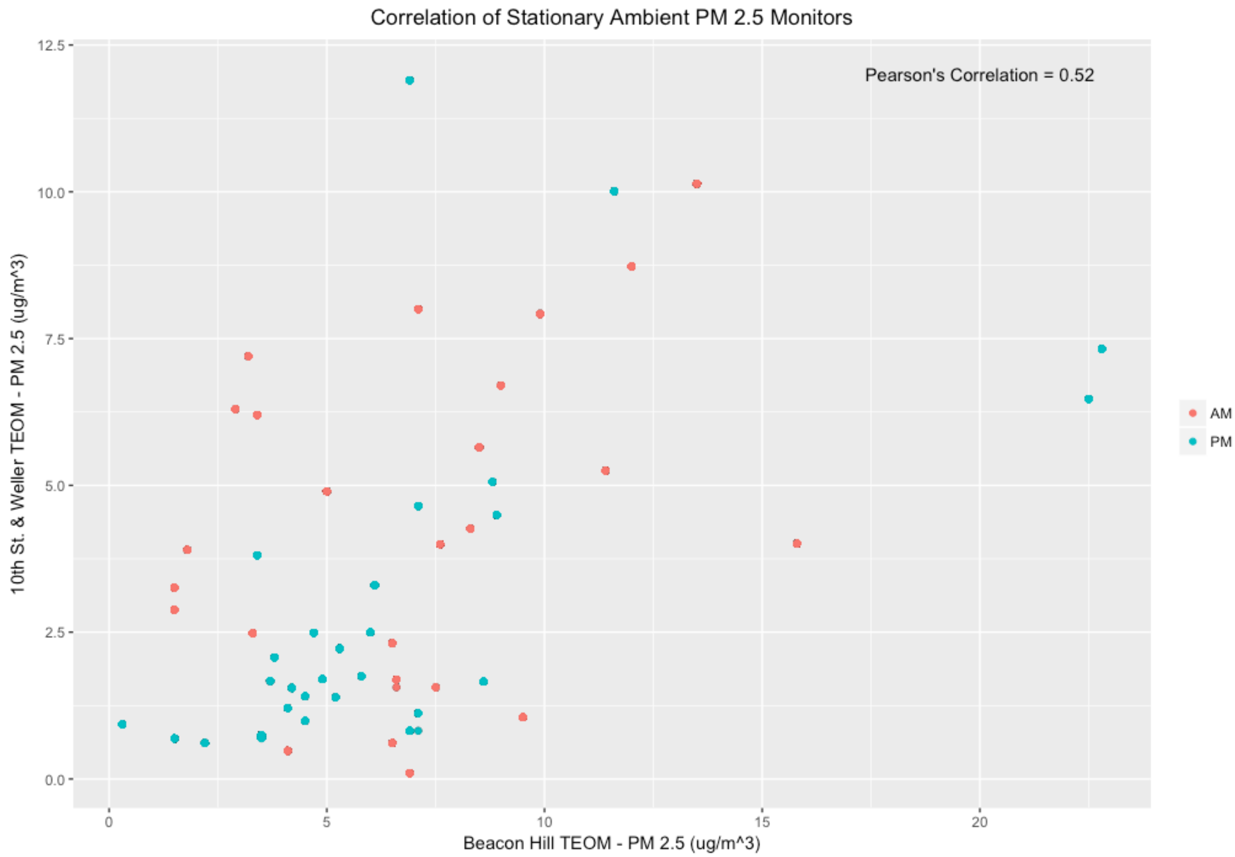
Map data © 2017 Google

Appendix II. Ambient $PM_{2.5}$ Monitor Locations

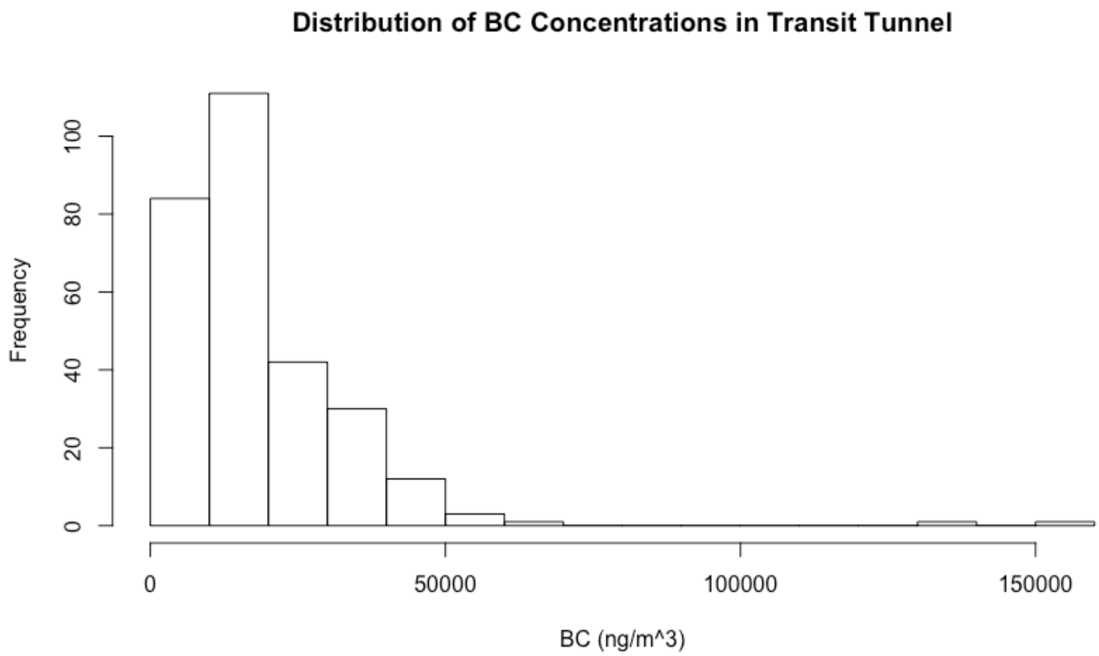


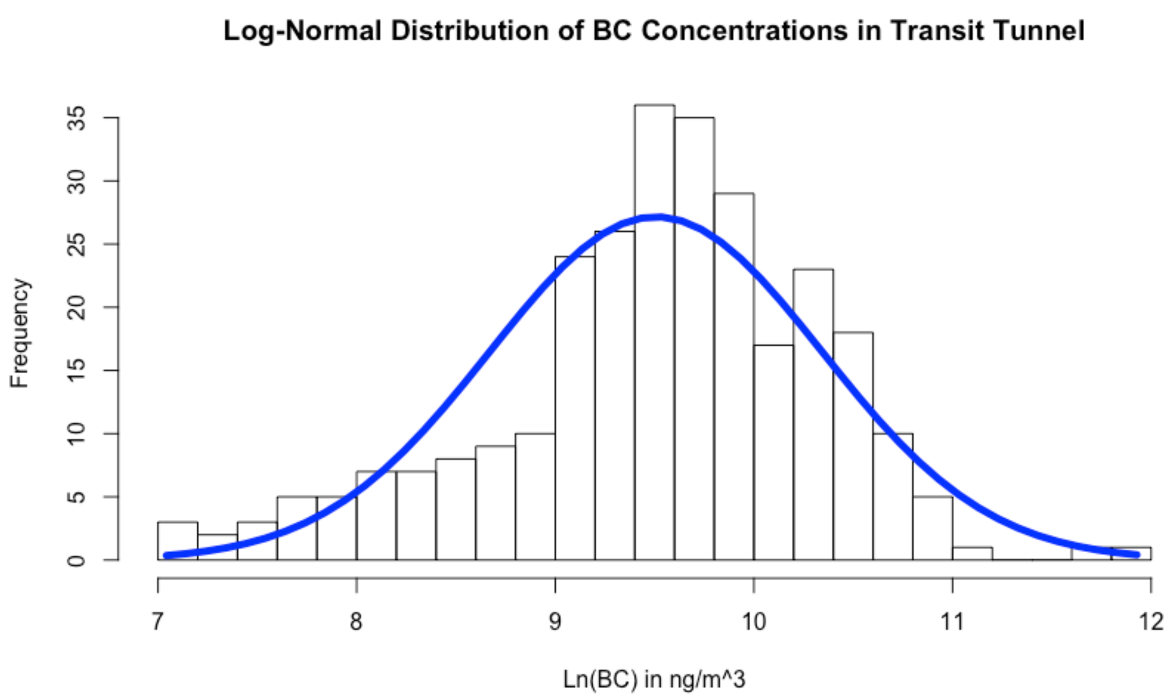
Map data copyrighted OpenStreetMap contributors and available from http://www.openstreetmap.org

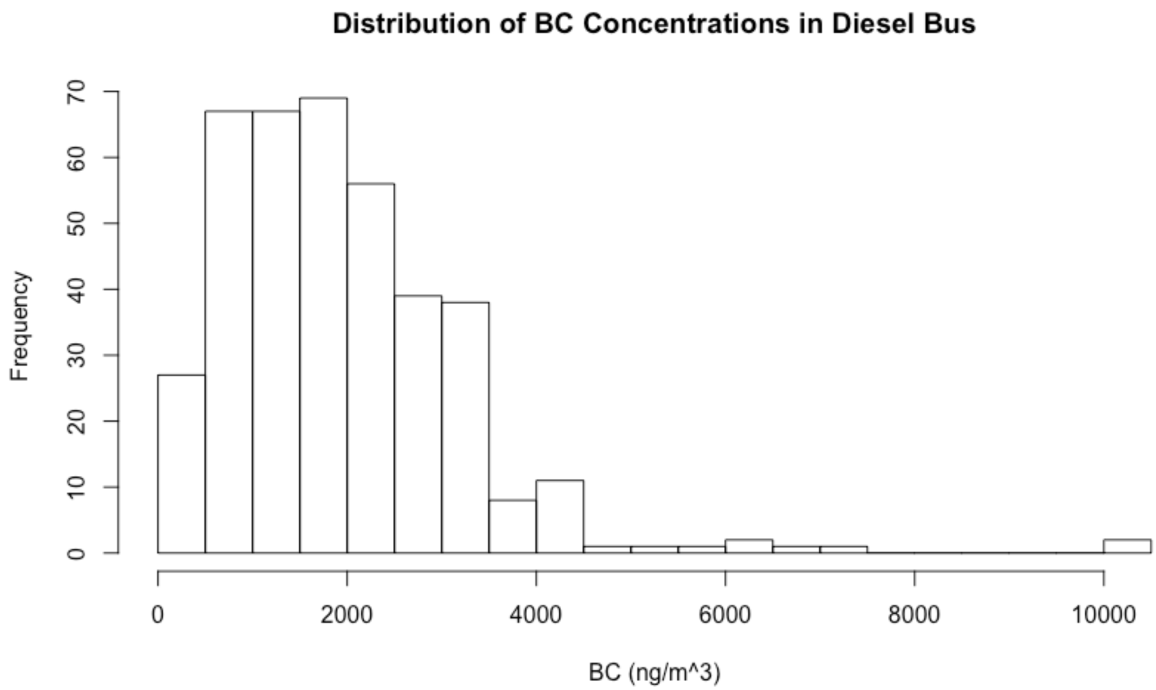
Appendix III. Correlation of Stationary Ambient $PM_{2.5}$ monitors considered for use in regression modeling.

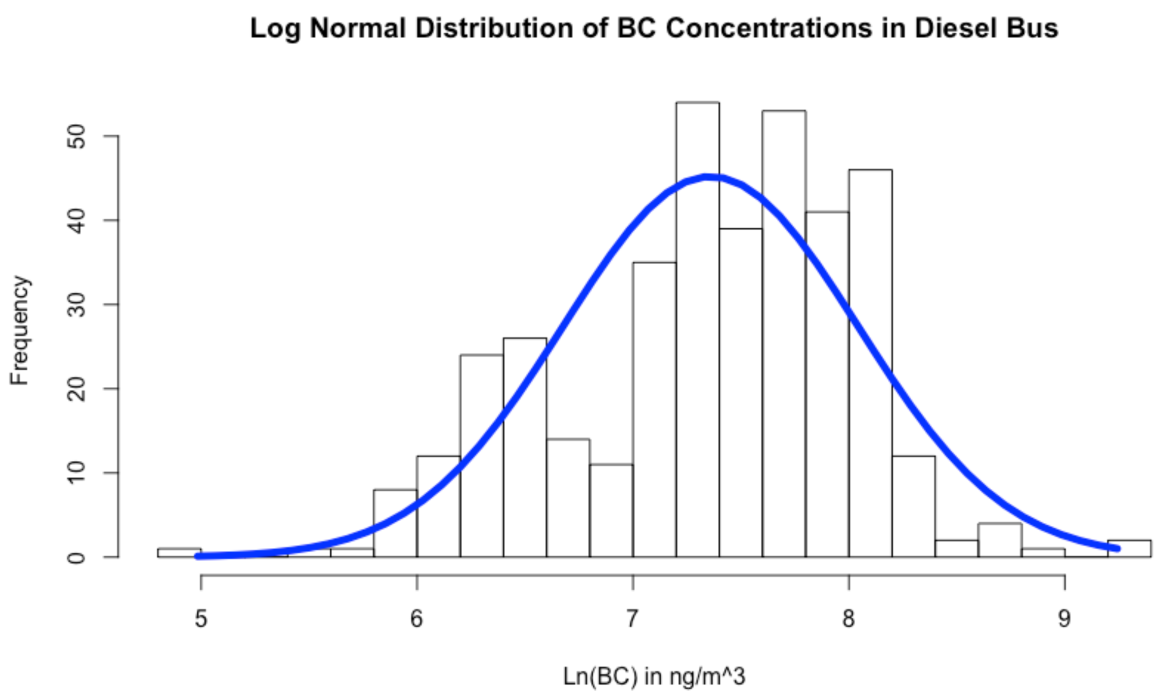


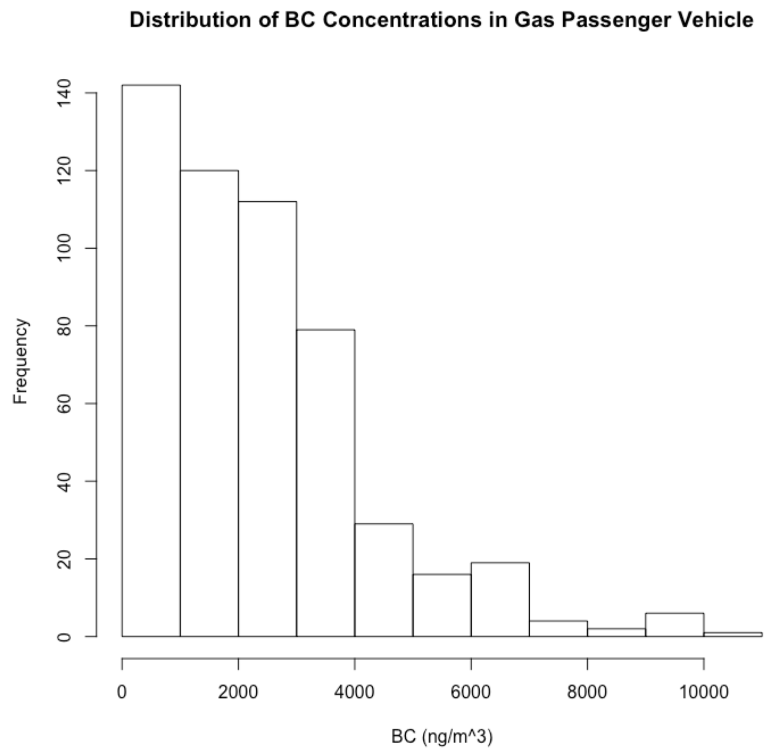
Appendix IV. Log-normality Assessments






Distribution of BC Concentrations in Diesel Bus
Frequency
0
10
20
30
40
50
60
70
0
2000
4000
6000
8000
10000
BC (ng/m^3)


Log Normal Distribution of BC Concentrations in Diesel Bus
Frequency
0
10
20
30
40
50
5
6
7
8
9
Ln(BC) in ng/m^3


Distribution of BC Concentrations in Gas Passenger Vehicle
Frequency
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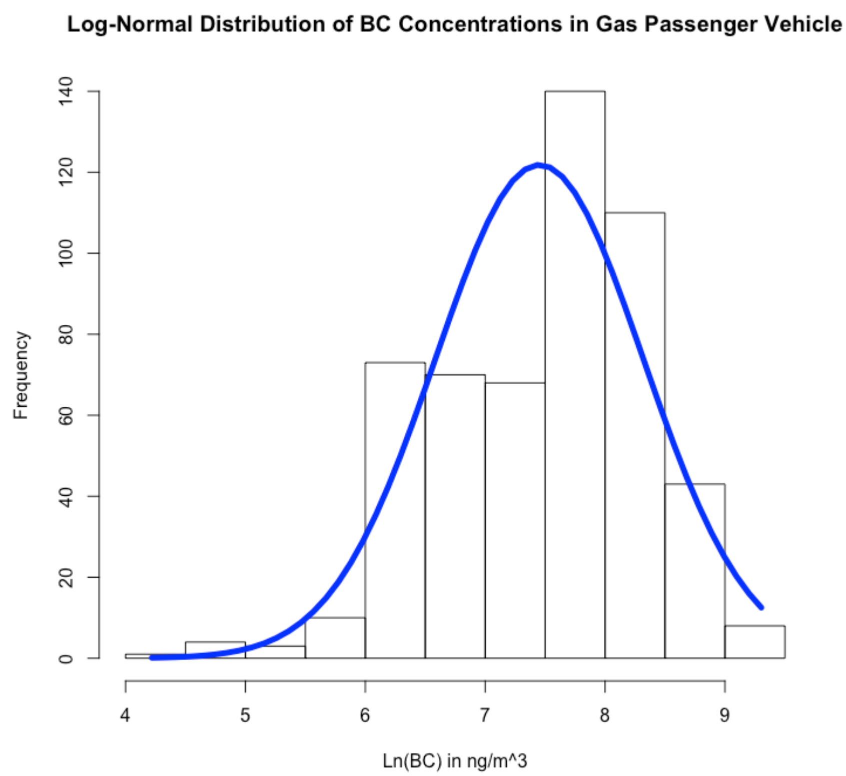
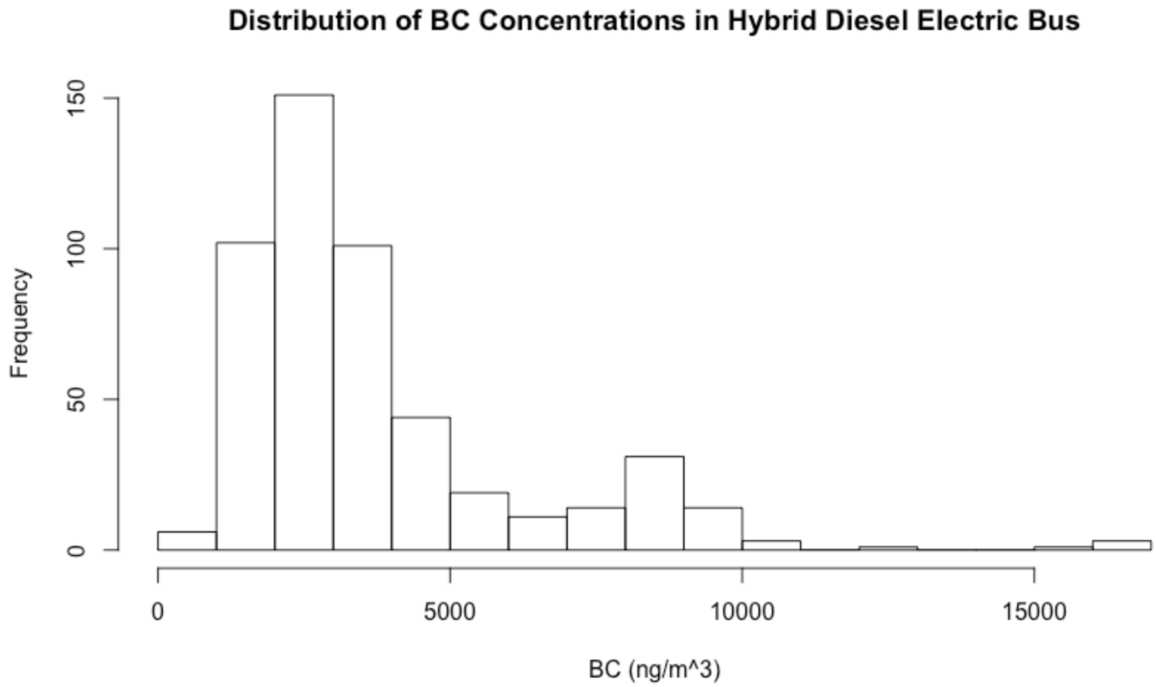
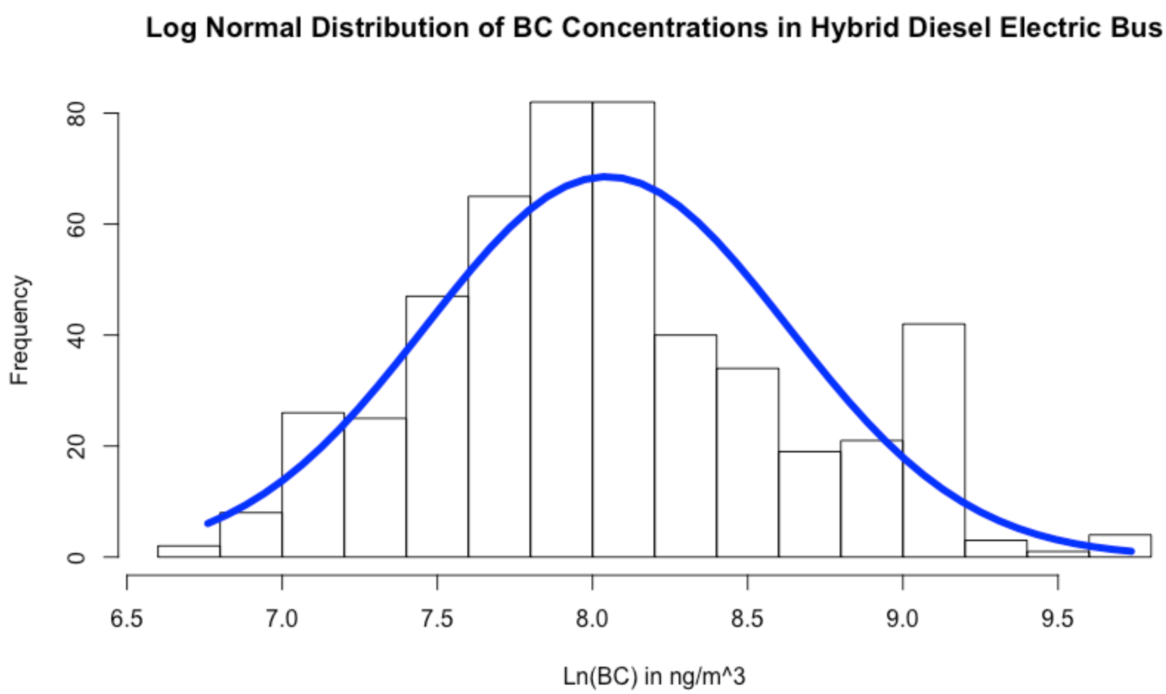
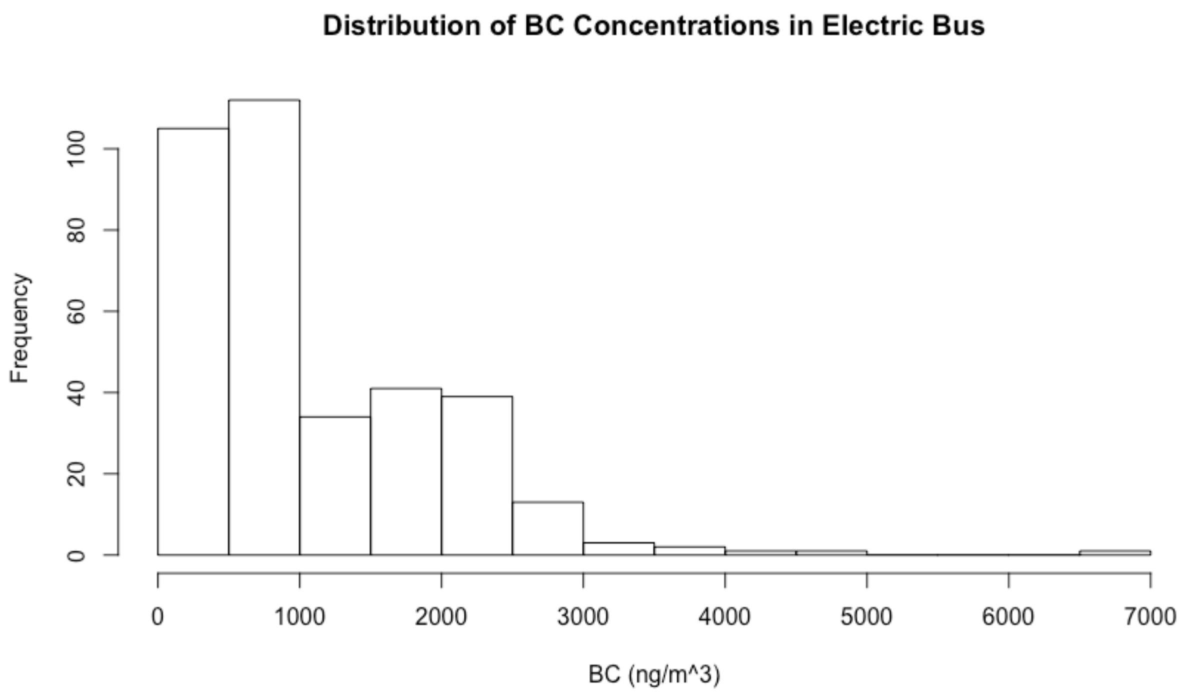
20
40
60
80
100
120
140
0
2000
4000
6000
8000
10000
BC (ng/m^3)


Log-Normal Distribution of BC Concentrations in Gas Passenger Vehicle
Frequency
0
20
40
60
80
100
120
140
4
5
6
7
8
9
Ln(BC) in ng/m^3


Distribution of BC Concentrations in Hybrid Diesel Electric Bus
Frequency
0
50
100
150
0
5000
10000
15000
BC (ng/m^3)


Log Normal Distribution of BC Concentrations in Hybrid Diesel Electric Bus
Frequency
0
20
40
60
80
6.5
7.0
7.5
8.0
8.5
9.0
9.5
Ln(BC) in ng/m^3


Distribution of BC Concentrations in Electric Bus
Frequency
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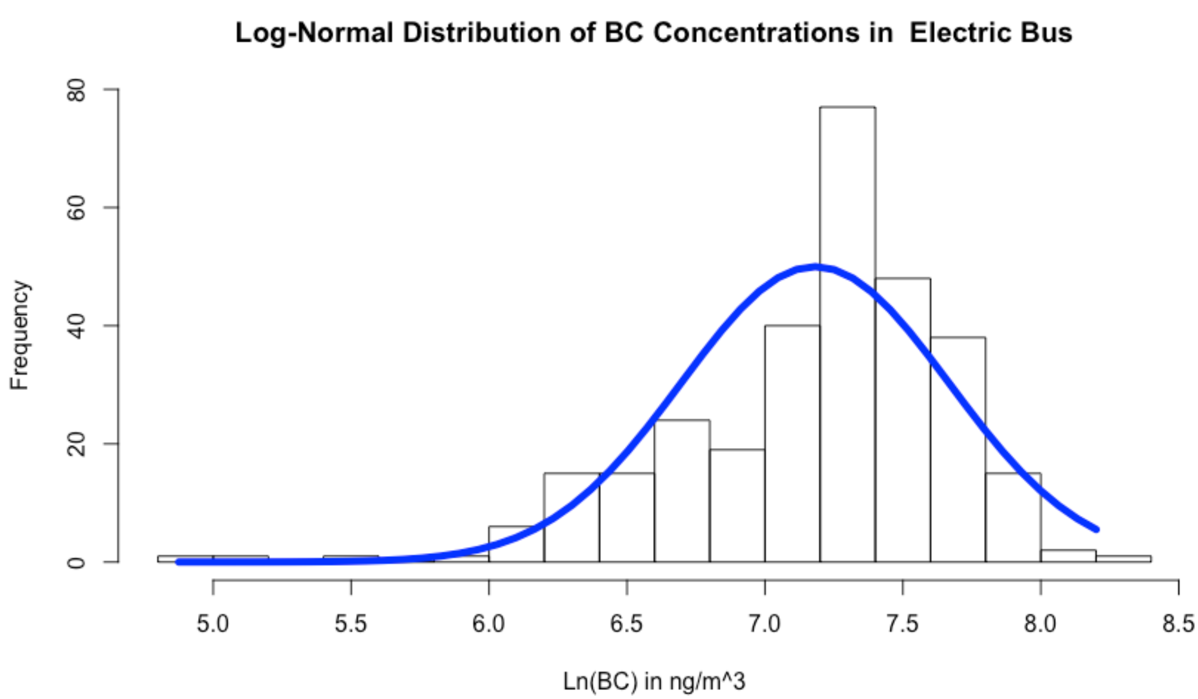
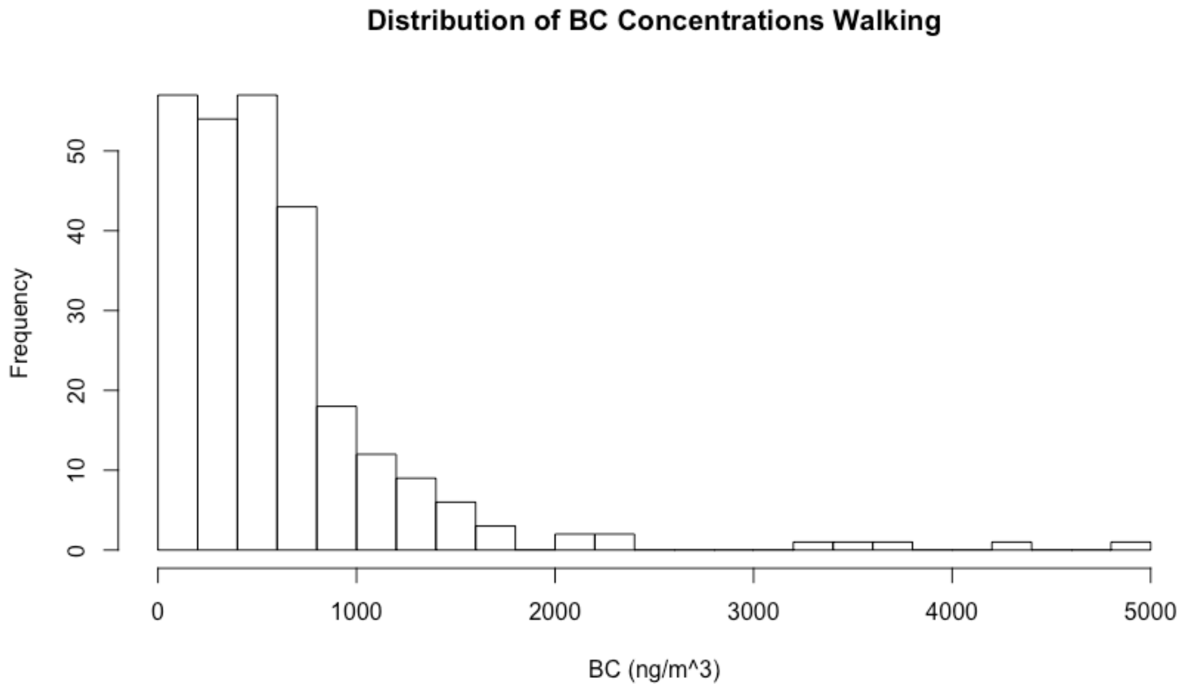
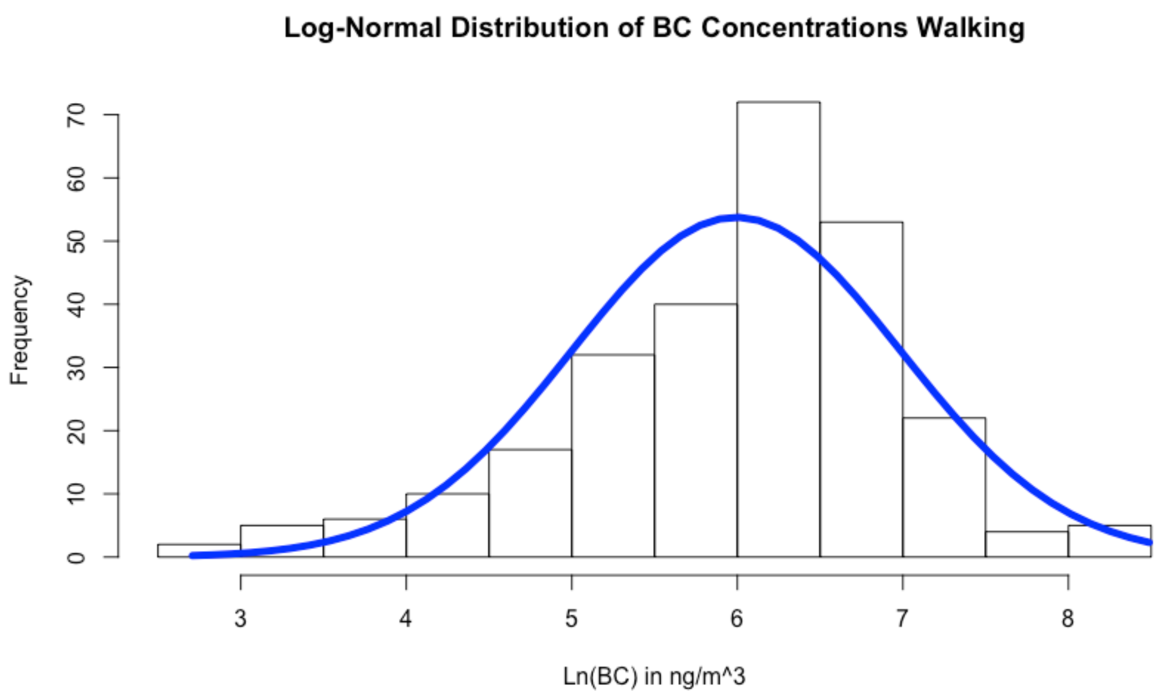
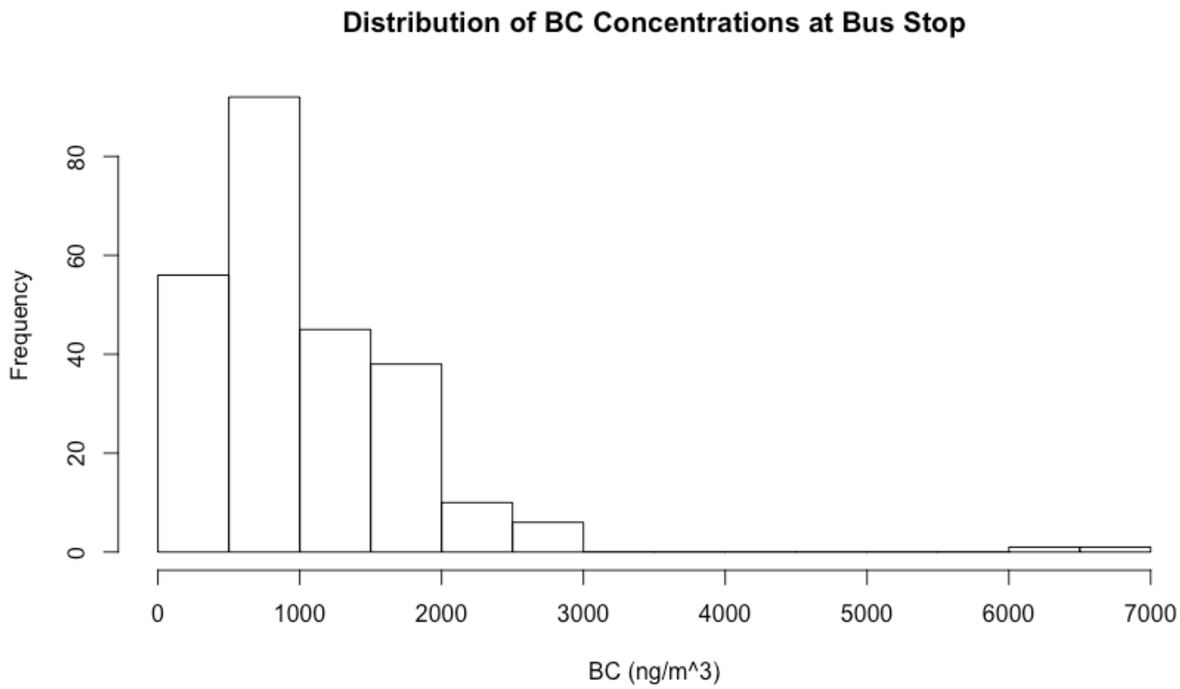
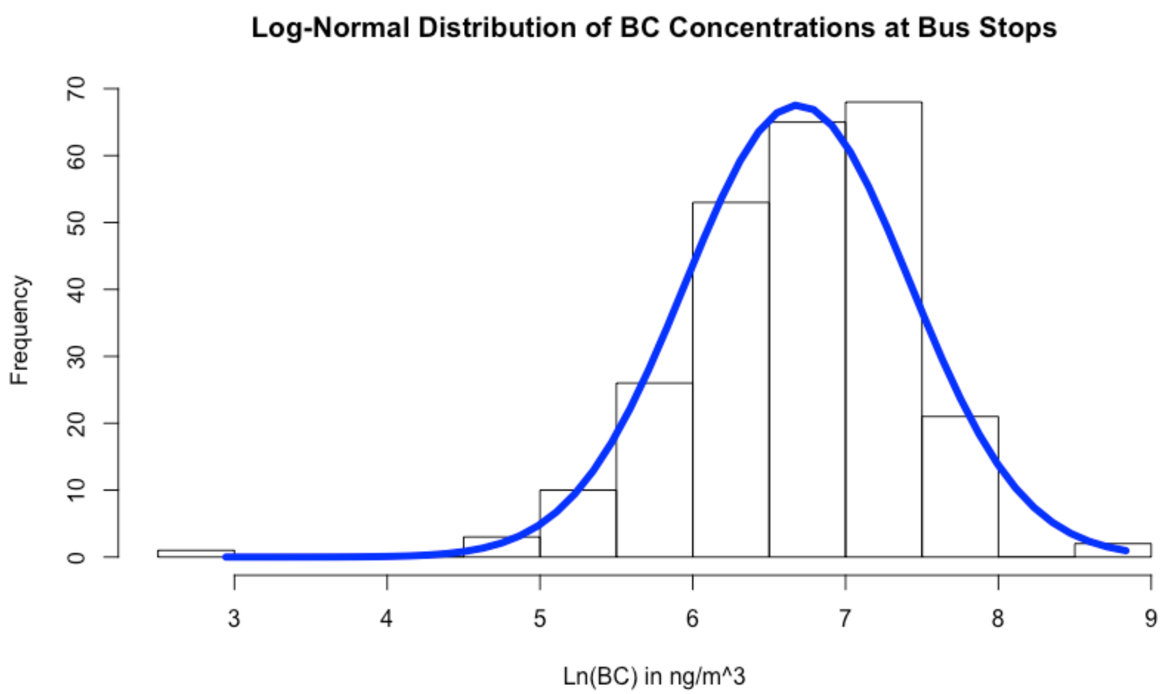
20
40
60
80
100
0
1000
2000
3000
4000
5000
6000
7000
BC (ng/m^3)

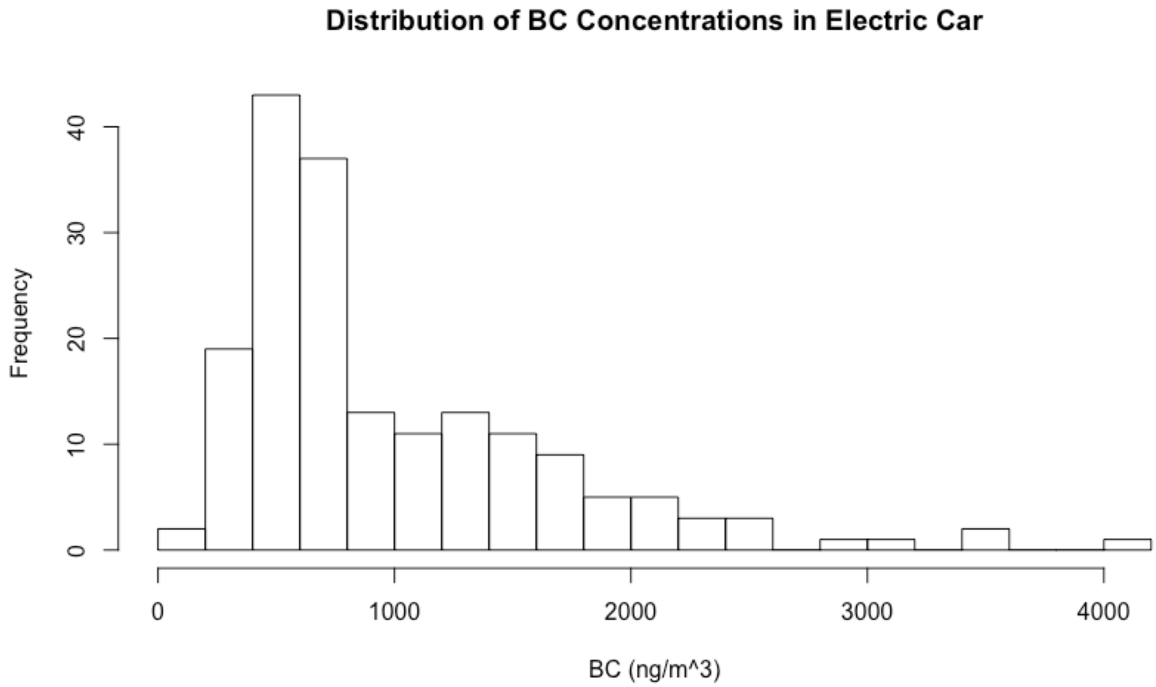

Log-Normal Distribution of BC Concentrations in Electric Bus
Frequency
0
20
40
60
80
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
Ln(BC) in ng/m^3

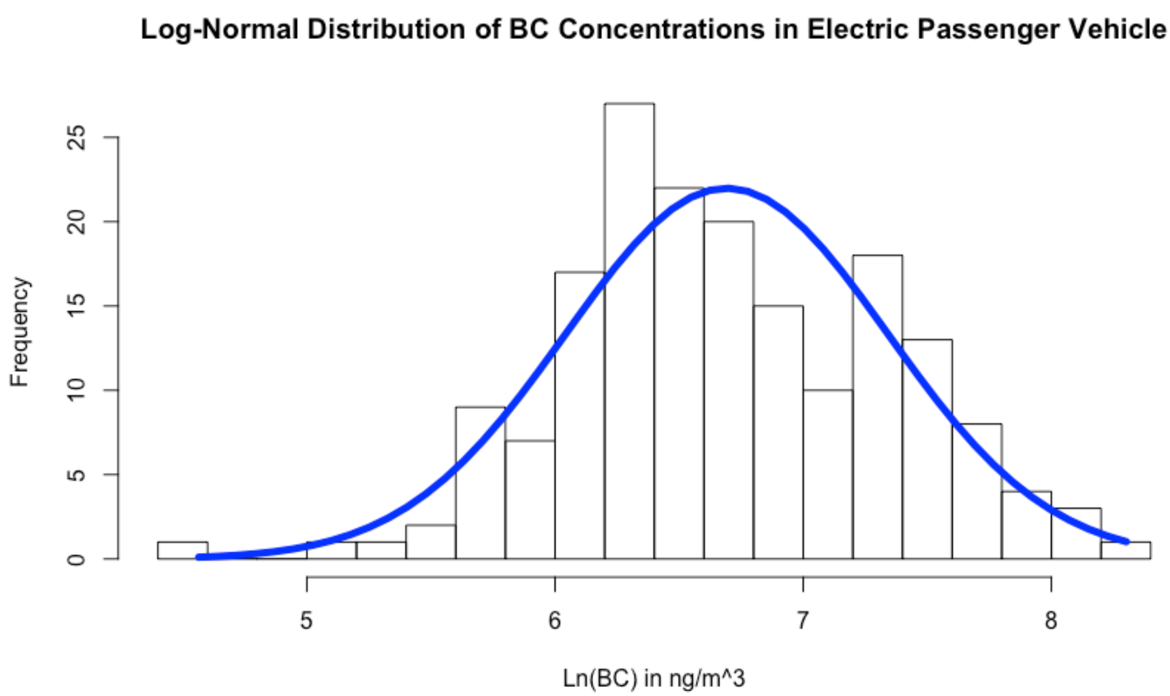

Distribution of BC Concentrations Walking
Frequency
0
10
20
30
40
50
0
1000
2000
3000
4000
5000
BC (ng/m^3)


Log-Normal Distribution of BC Concentrations Walking
Frequency
0
10
20
30
40
50
60
70
3
4
5
6
7
8
Ln(BC) in ng/m^3


Distribution of BC Concentrations at Bus Stop
Frequency
0
20
40
60
80
0
1000
2000
3000
4000
5000
6000
7000
BC (ng/m^3)


Log-Normal Distribution of BC Concentrations at Bus Stops
Frequency
0
10
20
30
40
50
60
70
3
4
5
6
7
8
9
Ln(BC) in ng/m^3


Distribution of BC Concentrations in Electric Car
Frequency
0
10
20
30
40
0
1000
2000
3000
4000
BC (ng/m^3)


Log-Normal Distribution of BC Concentrations in Electric Passenger Vehicle
Frequency
0
5
10
15
20
25
5
6
7
8
Ln(BC) in ng/m^3

Appendix V. Bus and Vehicle Types

Mode	Make	Model
Gas Powered Passenger Vehicle	Mazda	Mazda3
Electric Vehicle[a]	BMW	i3
Bus Rapid Transit[a]	New Flyer	Xcelsior XDE60
Hybrid Diesel-Electric Bus[a]	New Flyer	Xcelsior XDE40
	New Flyer	Xcelrios XDE35
	New Flyer	DE60LFR
	Orion	VII
	New Flyer	DE60LF
Diesel Bus[a]		
Electric Bus[a]	New Flyer	Xcelsior XT40

[a] Source: King County Metro, 2016