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Spatio-Temporal Analysis of the Roadside Transportation Related Air Quality (STARTRAQ) and Neighborhood Characterization

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CALIFORNIA STATE UNIVERSITY LONG BEACH

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Report 21-22

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16. Abstract

To promote active transportation modes (such as bike ride and walking), and to create safer communities for easier access to transit, it is essential to provide consolidated data-driven transportation information to the public. The relevant and timely information from data facilitates the improvement of decision-making processes for the establishment of public policy and urban planning for sustainable growth, and for promoting public health in the region. For the characterization of the spatial variation of transportation-emitted air pollution in the Fresno/Clovis neighborhood in California, various species of particulate matters emitted from traffic sources were measured using real-time monitors and GPS loggers at over 100 neighborhood walking routes within 58 census tracts from the previous research, Children's Health to Air Pollution Study - San Joaquin Valley (CHAPS-SJV).

Roadside air pollution data show that PM2.5, black carbon, and PAHs were significantly elevated in the neighborhood walking air samples compared to indoor air or the ambient monitoring station in the Central Fresno area due to the immediate source proximity. The simultaneous parallel measurements in two neighborhoods which are distinctively different areas (High diesel High poverty vs. Low diesel Low poverty) showed that the higher pollution levels were observed when more frequent vehicular activities were occurring around the neighborhoods. Elevated PM2.5 concentrations near the roadways were evident with a high volume of traffic and in regions with more unpaved areas. Neighborhood walking air samples were influenced by immediate roadway traffic conditions, such as encounters with diesel trucks, approaching in close proximity to freeways and/or busy roadways, passing cigarette smokers, and gardening activity. The elevated black carbon concentrations occur near the highway corridors and regions with high diesel traffic and high industry.

This project provides consolidated data-driven transportation information to the public including:

1. Transportation-related particle pollution data
2. Spatial analyses of geocoded vehicle emissions
3. Neighborhood characterization for the built environment such as cities, buildings, roads, parks, walkways, etc..

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Executive Summary

To promote active transportation modes (such as bike ride and walking), and to create safer communities for easier access to transit, it is essential to provide consolidated data-driven transportation information to the public. The relevant and timely information from data facilitates the improvement of decision-making processes for the establishment of public policy and urban planning for sustainable growth, and for promoting public health in the region. For the characterization of the spatial variation of transportation-emitted air pollution in the Fresno/Clovis neighborhood in California, various species of particulate matters emitted from traffic sources were measured using real-time monitors and GPS loggers at over 100 neighborhood walking routes within 58 census tracts from the previous research, Children's Health to Air Pollution Study - San Joaquin Valley (CHAPS-SJV).

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This project provides consolidated data-driven transportation information to the public including:

1. Transportation-related particle pollution data
2. Spatial analyses of geocoded vehicle emissions
3. Neighborhood characterization for the built environment such as cities, buildings, roads, parks, walkways, etc.

1. Introduction

To promote active transportation modes, such as bike rides and walking, and to create safer communities for easier access to transit, it is essential to provide to the public the consolidated data-driven transportation information of the stakeholders and the public. The relevant and timely information from data facilitates the improvement of decision-making processes for the establishment of public policy and urban planning, and for sustainable growth and promoting public health in the region.

Among many transportation-related data, this study establishes:

1. Transportation-related particle pollution data
2. Spatial analyses of geocoded vehicle emissions
3. Neighborhood characterization for the built environment such as cities, buildings, roads, parks, walkways, etc.

Transportation Emitted Air Pollutant Data: The vehicle transportation-related air pollution was measured at 150 neighborhood walking routes within 22 zip codes including 58 census tracts in the Fresno/Clovis area for over four years from the previous NIEHS/USEPA funded research, Children's Health to Air Pollution Study – San Joaquin Valley (CHAPS-SJV) with PIs of UC Berkeley, Stanford University and Fresno State. To characterize the spatial variation of transportation-emitted air pollution in the Fresno/Clovis neighborhood, various species of particulate matter emitted from traffic sources were measured using real-time monitors and GPS loggers. The pollutants include particulate matter (PM10, PM2.5, PM1), black carbon (BC), ultrafine particles, and polycyclic aromatic hydrocarbons (PAHs).

Spatial Analyses of Geocoded Data: Vehicle transportation, especially diesel trucks, is known as a major emission source of fine particulate matter (PM2.5). Black carbon and polycyclic aromatic hydrocarbons (PAHs) are the toxic components of fine particulate matter and the trace of diesel emission. The real-time concentrations of particulate species varying in different transportation sources will provide a remarkable insight to analyze the dynamic temporal impact on transportation-related pollution patterns. For aligning various pollutant concentrations synchronously over the accurately geocoded neighborhood locations from the walking routes, quality assurance and quality control (QA/QC) from the pollution and positional data are necessary.

Neighborhood Characterization: Secondary data indicators characterizing built environment, transportation choices, and general health risks such as walkability and socioeconomic factors are available for each census tract where the neighborhood walking routes are contained (i.e., Walk score and CalEnvironScreen scores, etc.). Therefore, the geospatial analysis of the transportation-related pollution by different roadway classes, land-use, meteorological conditions, and socioeconomic status of the neighborhoods will be possible as a result of the geospatial data consolidation.

The objectives of this study are to provide:

1. Pollution sensor calibration and evaluation of a low-cost pollution sensor
2. Spatial analysis of pollution data
    a. Impact of transportation-related particulate matters on the roadside air quality in Fresno, CA
    b. The relationship of particulate matter near roadways and zip code, taking into account spatial-temporal factors and analysis of health effects in Fresno, CA

2. Background

The San Joaquin Valley, and Fresno in particular, are identified as areas for having high levels of particulate matter that go above federal and state clean air standards (EPA 2019). Many of the cities in the 8-county region, such as Fresno, are classified as the most polluted cities in the United States for both particulate matter and ozone pollution. (American Lung Association, 2021). Particulate matter, specifically those with a diameter of 2.5 micrometers (PM2.5), has been known to pose a risk to human health. While many PM2.5 particles vary in compositions, black carbon (BC) which occurs due to incomplete combustion from gas and diesel engines and other sources, make up a majority of particulate matter emitted worldwide (Bessagnet & Allemand, 2020). As toxic components of particulate matters, black carbon, polycyclic aromatic hydrocarbons (Noth, et al., 2011) emitted from the fossil fuel combustion, mainly from transportation mobile sources, are associated with increased health effects including high levels of hospital admittance and emergency room visits linked to asthma complications, increased cardiovascular disease risks, and even premature death.

Contributors to high levels of air pollution in Fresno are partly due to the geography and weak winds present in the San Joaquin Valley; the valley is surrounded by mountains (the Sierra Nevada, Tehachapi Mountains, and Coastal Range mountains) that act as a barrier preventing air from leaving. Weak winds further prevent air from escaping the valley, thus increasing the concentration of pollutants as illustrated in Figure 1 (Noth et al., 2011). Local contributors to PM2.5 in Fresno include major roads such as California State Routes 41, 99, 168, & 180 (City of Fresno, 2014) as well as other local sources. Figure 2 illustrates the roadways and bike and walking trails in the Fresno area.

Figure 1. Typical Wind Patterns in San Joaquin Valley Air Basin (Noth et al 2011)

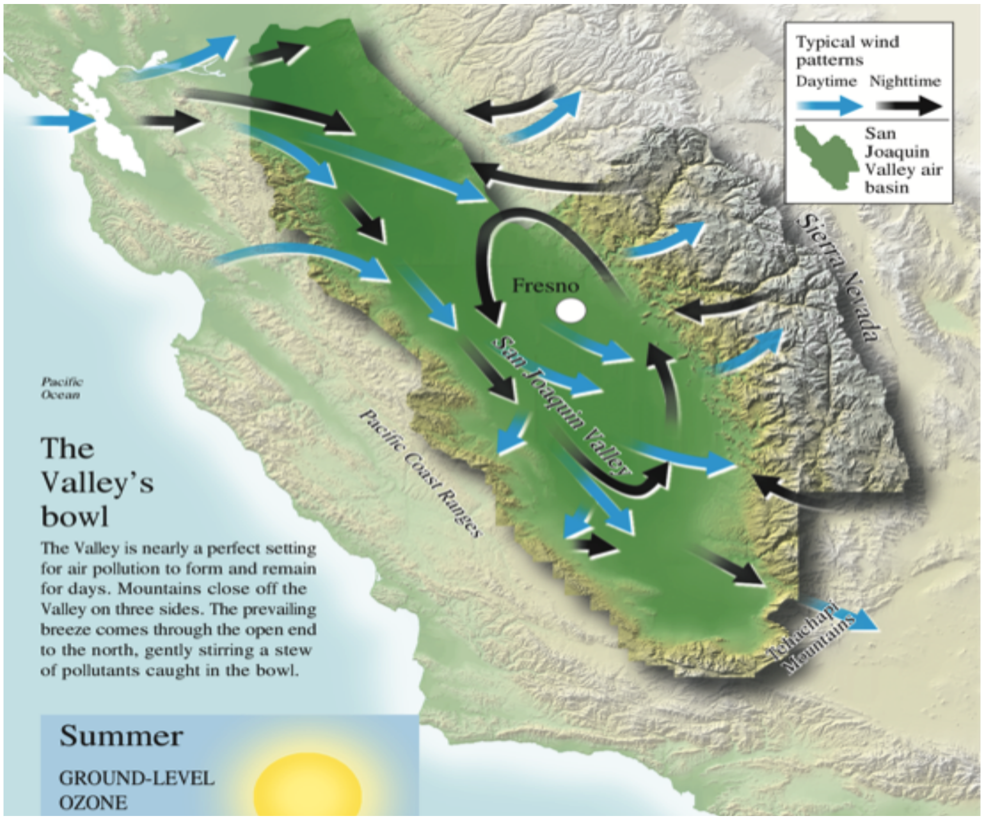
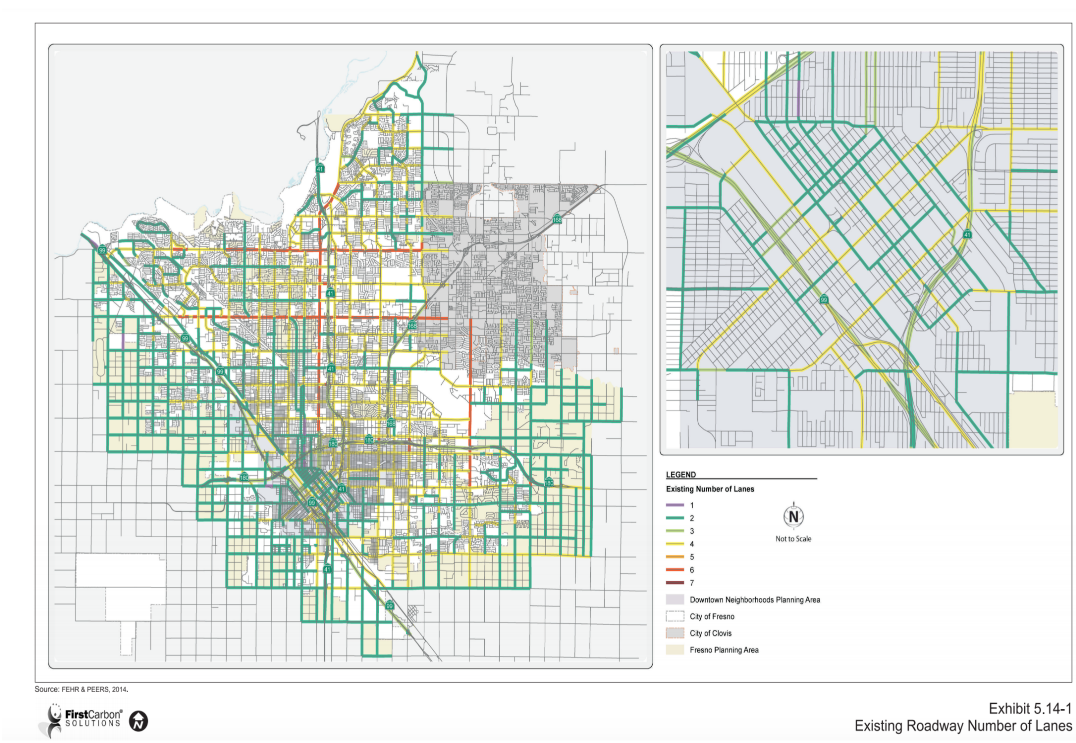
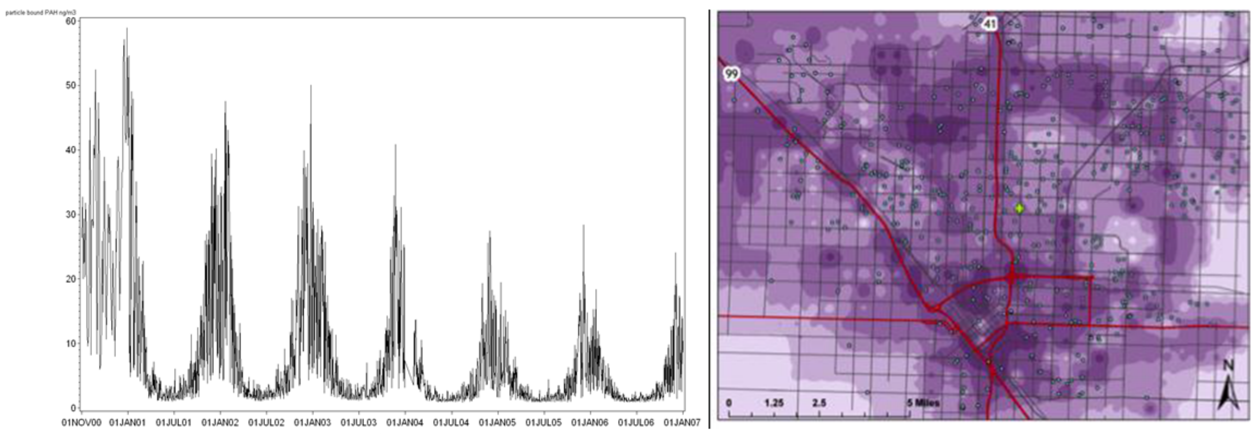


Figure 2. Map of Major Roadways and Existing Number of Lanes in Fresno (City of Fresno, 2014)



Previous studies have shown elevated levels of particulate matter occurring near roads due to emissions from cars and trucks. These particles are small enough to be inhaled and can cause irritation in the lungs and trouble breathing. Increased levels of particulate matter and exposure have shown an increase in levels of asthma and hospitalization as a result (Alcala et al., 2019). Padula et al. (2018) conducted in the San Joaquin Valley have also shown that mothers exposed to elevated levels of air pollutants, specifically particulate matter, were twice as likely to deliver a baby prematurely. In Fresno County alone, an estimated 12.1% of the population had increased levels of preterm birth, a statistic significantly higher than the state level of 9.6 % (Padula et al., 2018). There has also been an association between pollutants emitted by road traffic and increased levels of hypertension (Weber et al., 2019) that can also decrease the quality of life for individuals exposed to elevated levels of air pollutants. The pollutants that occur near these roads are dependent on the level of traffic, temperature, and wind to further disperse pollutants to communities (Baldauf et al., 2009).

Figure 3. Daily PAHs in Fresno for 7 Years (left), Spatial Variability of PAHs in the FACES - Fresno Asthmatic Children's Environment Study (right) (Noth et al., 2011)



3. Methodology

3.1 Roadside Transportation-Related Particulate Air Quality Data

The roadside transportation-related air pollutant concentrations were measured using various real-time air quality monitors and Global Positioning System (GPS) loggers during the Children's Health to Air Pollution Study in San Joaquin Valley (CHAPS-SJV). One of the objectives of CHAPS-SJV was to examine neighborhood characteristics that have a direct and quantifiable relationship with an individual's transit patterns that in turn affect personal exposures to traffic-related air pollution (PAHs, $PM_{2.5}$, and BC) (Figure 4). The transportation-emitted pollutants include particulate matter (PM10, PM2.5, PM1), black carbon (BC), ultrafine particles, and polycyclic aromatic hydrocarbons (PAHs). The pollution concentrations quantified by the multiple air monitors for specific particle pollutant of concern are as follow: DustTrack DRX Aerosol (8533, 8534, TSI Inc., Shoreview, MN) monitors for the particulate matter mass concentrations for PM10, PM2.5, and PM1; condensation particle counter (CPC 3007, TSI Inc., Shoreview, MN), microAeth AE51 personal exposure nephelometers (AethLabs, San Francisco, CA) for black carbon concentrations; and portable compact photoelectric aerosol sensors (PAS 2200CE, League City, TX) for PAHs. The GPS loggers (Trackstick, Telespial Systems, CA) recorded the GPS position data synchronously with the real-time air quality monitors during the air quality sampling. Because the zip codes in Fresno have a highly varying total area, area density, and area population, each zip code was divided into 3-5 sub-sections based on distances from the zip centroid and population density. The routes of 1.5-2 miles, representing 10 block faces (segments) were each selected for both neighborhood air pollution exposure and social structure observation (SSO) over the Fresno/Clovis area. Student assistants walked the route of the neighborhoods on each block carrying the real-time air pollutant measurement instruments on the strollers from January 2015 to June 2017. Overall, 96 route samples have been completed from 22 zip code areas (Table 1). In addition, three routes that had the highest PAHs levels at the first sampling were simultaneously sampled three times, along with the routes that had the lowest PAHs levels at the first sampling. Including the 54 repeated measures, 150 routes were sampled for the concentration of air pollutants. The starting location of the routes that were sampled is shown in Table A-1 (appendix).

Figure 4. Relationship Among the Mode of Transportation, Built Environment, and Air Pollution.

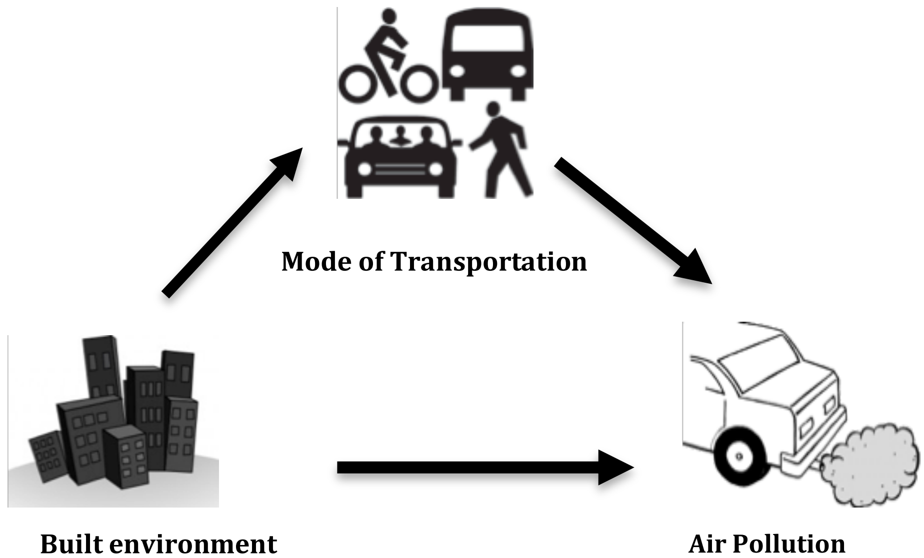


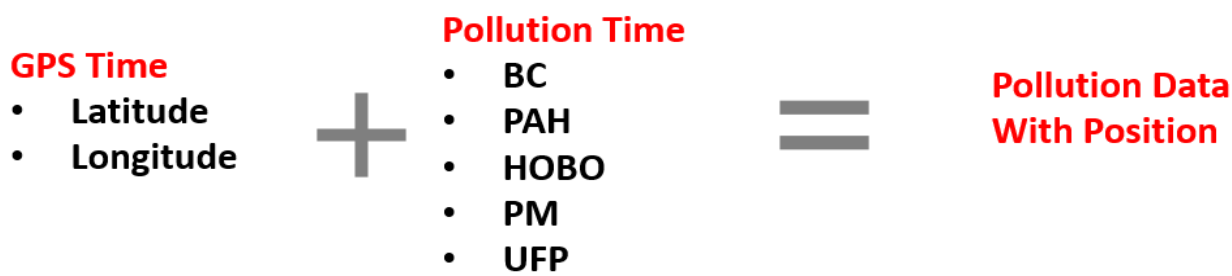
Table 1. Summary of Real-time Mobile Monitoring at Structured Social Observation (SSO) Route Samples Collected

Batch ID	SSO	Air Pollution	New Zip Code	Routes	Pollution samples	Sample number
Batch 1	2014 Fall	2015 Spring	3	10	repeated	20
Batch 2	2015 Spring	2015 Spring	3	10	repeated	20
Batch 3	2015 Fall	2016 Spring	3	13	one time	13
Batch 4	2016 Spring	2016 Spring	4	13	one time	13
2016 Spring, Two routes repeated 7 times (High diesel High poverty vs. Low diesel Low poverty)						14
Batch 5	2016 Summer	2017 Spring	8	27	one time	27
Batch 6	2017 Summer	2017 Spring	1	23	one time	23
2017 Spring, two routes from Batch 4 were sampled again for CART students						2
2017 Spring, six routes from Batch 5 and 6 were sampled three times						18
Total			22	96		150 routes

3.2 Roadside Air Quality Sensor Data Assimilation for Geospatial Analysis

Roadside transportation air quality was utilized for geospatial analysis and GPS positioned and polarized pollutant concentrations. The raw data were processed and organized in a way that positional data from GPS and quality-assured pollution concentrations are synchronized, followed by basic filtering (Figure 5 & 6). Roadside pollution changes in time and along the trajectories. Therefore, the relationship among the pollution levels with transportation and environmental factors such as speed, roadway classifications, and land use around the road can be produced by a 3D representation of results in Matlab and ArcGIS for each sampled location (Figure 7).

Figure 5. The Concept of Data Synchronization

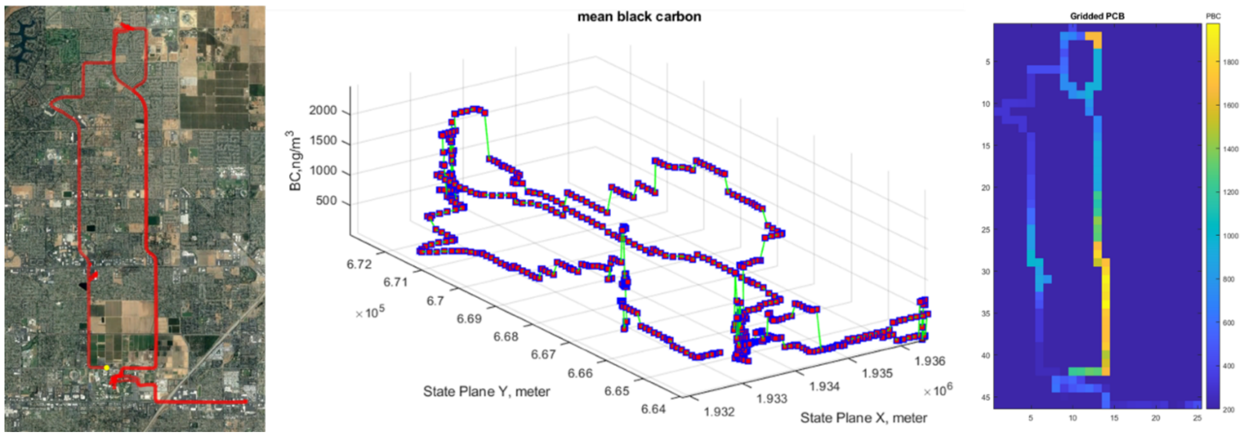


Most of the pollution sensors contain timestamps and pollution content such as PM2.5. In order to perform spatial analysis, GPS location information needs to be utilized in accordance with other pollution data. Based on GPS time, other pollution data time is searched if that data falls in the GPS 1-minute bin. The binned data are averaged to match GPS location data.

Figure 6. An Example of Time-Synchronized Data. A Single Position can have Multiple Pollution Data for Further Geospatial Analysis.

Year	Mon	Day	Hour	Min	Sec	X	Y	Lon	Lat	BC	HOBO	PAH	PM	PM	PM	UFP
2015	1	30	14	54	0	1933130	661534.7	-119.749	36.78675	2513	50.51	72.83333	0.095333	0.024	0.097	5798.75
2015	1	30	14	56	0	1933144	661532.3	-119.749	36.78673	1317	50.61767	5.833333	0.0945	0.024	0.096333	5435.25
2015	1	30	14	57	0	1933173	661533.2	-119.749	36.78674	861	51.06683	9.666667	0.093667	0.023	0.095833	11221.25
2015	1	30	14	58	0	1933223	661535.1	-119.748	36.78676	1145	51.7555	51.83333	0.094167	0.024	0.095167	8514.25
2015	1	30	14	59	0	1933280	661532.4	-119.748	36.78674	1129	51.27167	39.33333	0.093333	0.024	0.094667	7297.75
2015	1	30	15	0	0	1933342	661530.8	-119.747	36.78673	143	51.58383	80	0.094833	0.024	0.094833	6282.25
2015	1	30	15	1	0	1933408	661530.6	-119.746	36.78673	3469	51.81067	80.16667	0.090167	0.023	0.095167	3910.5
2015	1	30	15	8	0	1933466	661511.3	-119.745	36.78656	1119	51.44917	63.16667	0.088167	0.022	0.087333	4167.5
2015	1	30	15	9	0	1933466	661465.1	-119.745	36.78615	1197	51.34133	49.33333	0.087333	0.022	0.087833	4279.75
2015	1	30	15	10	0	1933466	661407	-119.745	36.78562	1455	51.6195	45.66667	0.086167	0.021	0.087333	3702
2015	1	30	15	11	0	1933475	661348.6	-119.745	36.7851	1604	51.43883	43.83333	0.084667	0.021	0.0865	3478.75
2015	1	30	15	12	0	1933548	661335.3	-119.745	36.78498	2014	51.40633	64.83333	0.084167	0.021	0.085167	3974.75
2015	1	30	15	13	0	1933570	661300.4	-119.744	36.78467	1185	52.01067	20.66667	0.084167	0.021	0.085167	3544
2015	1	30	15	14	0	1933569	661235	-119.744	36.78408	1359	52.20283	23.66667	0.083667	0.021	0.085	3734.75
2015	1	30	15	15	0	1933569	661173.9	-119.744	36.78353	1670	52.342	26.16667	0.082833	0.021	0.084333	3371.25

Figure 7. Example of Geo-Coded Pollution Data. (Left) The Trajectory of Black Carbon Concentration Along Local Roads, Fresno CA. (Middle) Black Carbon Concentration Geocoded from the Trajectory. (Right) Gridded Black Carbon Concentration.



3.3 Neighborhood Characteristic Data (Secondary data)

The secondary environmental indicator data were collected to characterize assets (e.g., bus stops/routes, sidewalks, food outlets, etc.) and liabilities (e.g., neighborhood foreclosure rate, the density of condemned properties, Toxic Release Inventory sites, high-speed surface street traffic, etc.) of the local built environment using the structured social observation (SSO) tools and data from CalEnviroScreen (a mapping tool developed by California's Environmental Protection Agency in order to identify areas with high levels of pollution) during the CHAPS-SJV. The secondary indicators acquired and analyzed for this project are listed below.

- Walk Score®: uses GPS data to assess neighborhood walkability considering nearby amenities and transportation. The average for Fresno is 42 (and for comparison, Berkeley CA has an average score of 79). The data set prepared by https://www.walkscore.com is unique to this project and represented a new application for Walk Score. Range: 0 to 100.
- CES (CalEnviroScreen) Pollution Burden Score: Considers exposures and environmental effects. Range: 0.1 to 10.
- CES (CalEnviroScreen) Population Characteristics Score: Considers sensitive populations and socioeconomic factors. Range: 0.1 to 10.
- CalEnviroScreenScore: Pollution Burden X Population Characteristics. Score: up to 100.
- Disorder-Walking (SSO): considers 16 possible indicators of social disorder and barriers to walking, such as condoms and syringes on street, abandoned homes, adults being hostile, no safe place to walk, etc.

- Order-Walking (SSO): considers 13 indicators of possible social order and supports for pedestrians such as streetlights, sidewalks, well-maintained empty lots, clearly marked crosswalks, etc.
- Environmental and Health Effect Data (CalEnviroScreen): to identify zip codes with high levels of traffic, diesel, asthma, and low birth rates in the Fresno/Clovis Area.

3.4 Spatio-Temporal Analysis of Roadside Air Quality

Time series analysis attempts to model the future in terms of previously observed values, and it has often been used to examine air pollution data. The particulate matters such as PM10, PM2.5, PM1, black carbon (BC), ultrafine particles, and polycyclic aromatic hydrocarbons (PAHs) are time-series data, and hence, understanding the time dependency is crucial for this project.

To characterize the spatial variation of air pollution in the Fresno/Clovis neighborhood, we will also employ a spatio-temporal framework to examine the variability through generalized additive models (GAM). GAM has been used in practice for many years in many different fields such as biology, engineering, health science, and business. Figures 8 and 9 illustrate the general concept of how the model is used.

Figure 8. Spatio-temporal Data Analysis Workflow

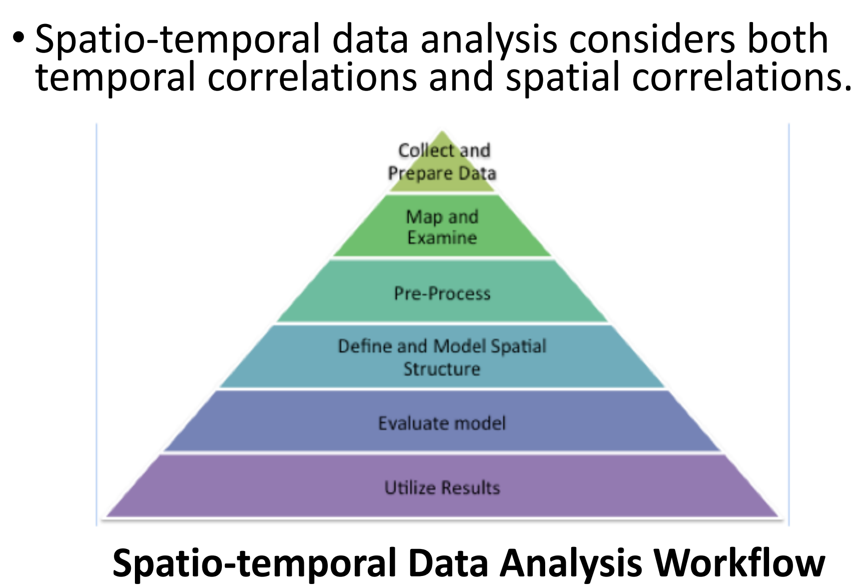
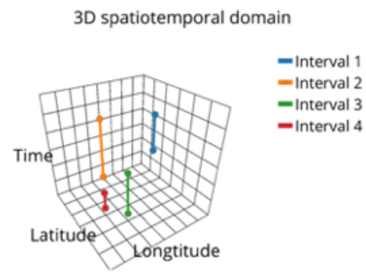


Figure 9. Spatio-temporal Model Schemes

Spatio-Temporal Model:

$$\boldsymbol{Y(s,t) = \mu(s,t) + v(s,t) + \varepsilon(s,t)},$$

$Y(s,t)$: observations
$\mu(s,t)$: mean
$v(s,t)$: zero-mean spatio-temporal process
$\varepsilon(s,t)$: white noise (usually Gaussian distribution).



<u>Example</u>: $$Y = X\theta + v + \varepsilon,$$
where $v \sim N(0, \sigma_v^2 \Sigma_v)$ and $\varepsilon \sim N(0, \sigma^2 D)$

3.5 Evaluation of low-cost Sensors in Field application

Due to increasing public interest and awareness of air pollution, there are several low-cost portable air monitoring sensors available in the market. We tested the two different types of monitoring sensors, Dylos and AtmoTube Pro, which have been used not only by scientists but also by communities for citizen science projects collecting personal exposure to particulate matters. The low-cost particulate matter monitoring sensors evaluated are: Dylos DC1700 (Dylos Corp., Riverside, CA), and Atmotube Pro (Atmotech Inc., San Francisco, CA) (Figure 10). Dylos DC1700 is a laser particle counter with two size ranges of particulate matter, PM10, and PM2.5. Atmotube Pro is also an optical PM sensor, based on laser scattering for PM10, PM2.5, and PM1. Atmotube Pro has the TVOC (Total Volatile Organic Compounds) which can be useful to measure evaporative organic compounds such as benzene and toluene from gasoline and solvents. We validated the performance of low-cost sensors by the side-by-side comparison of the collected particulate concentrations with the conventional methodology we use for measuring roadside transportation air quality.

Figure 10. The Real-Time Portable Air Quality Monitoring Sensors: DRX Dusttrack 8533 Aerosol Monitors (TSI Inc., Shoreview, MN); Dylos DC1700 (Dylos Corp., Riverside, CA); Atmotube Pro (Atmotech Inc., San Francisco, CA); And Tracksticks.

4. Summary & Conclusions

4.1 Roadside Transportation-Related Air Quality

The distribution of the walking route trailheads in the Fresno/Clovis area by zip codes is illustrated in Figure 11. The descriptive statistics of the particle concentrations from the CHAPS-SJV project are summarized in Table 2. For accurate spatial data analysis, the algorithm of data consolidation was developed to combine multiple pollutants at accurate times and locations to represent the pollutant levels at the same log intervals. Then, the quality assurance and quality control (QA/QC) procedure to identify errors for review were developed. When pollution concentration data are aligned accurately within the same log interval, the levels of different particulate species and their compositional ratios between the particle species could be calculated by the roadways; this calculation was used to investigate the immediate potential emission sources from the roadside air quality data for corresponding sampling periods. Time series plot examples for black carbon (BC) and polycyclic aromatic hydrocarbons (PAHs) concentrations at a road-side walking route is a good example of this process (Figure 12).

Figure 11. Trailheads Of The Transportation-Related Air Quality Monitored Walking Routes And Zip Codes In The Fresno/Clovis Area.

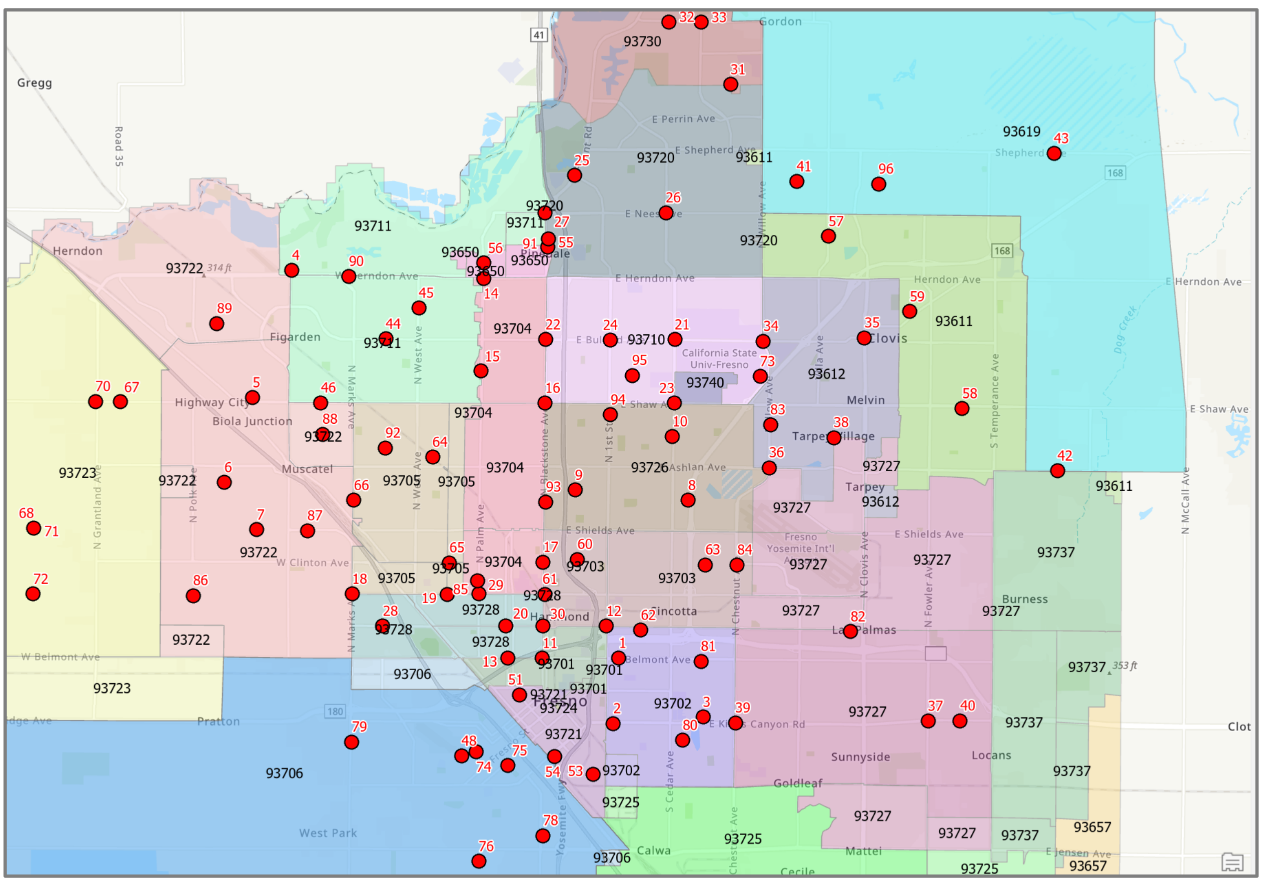
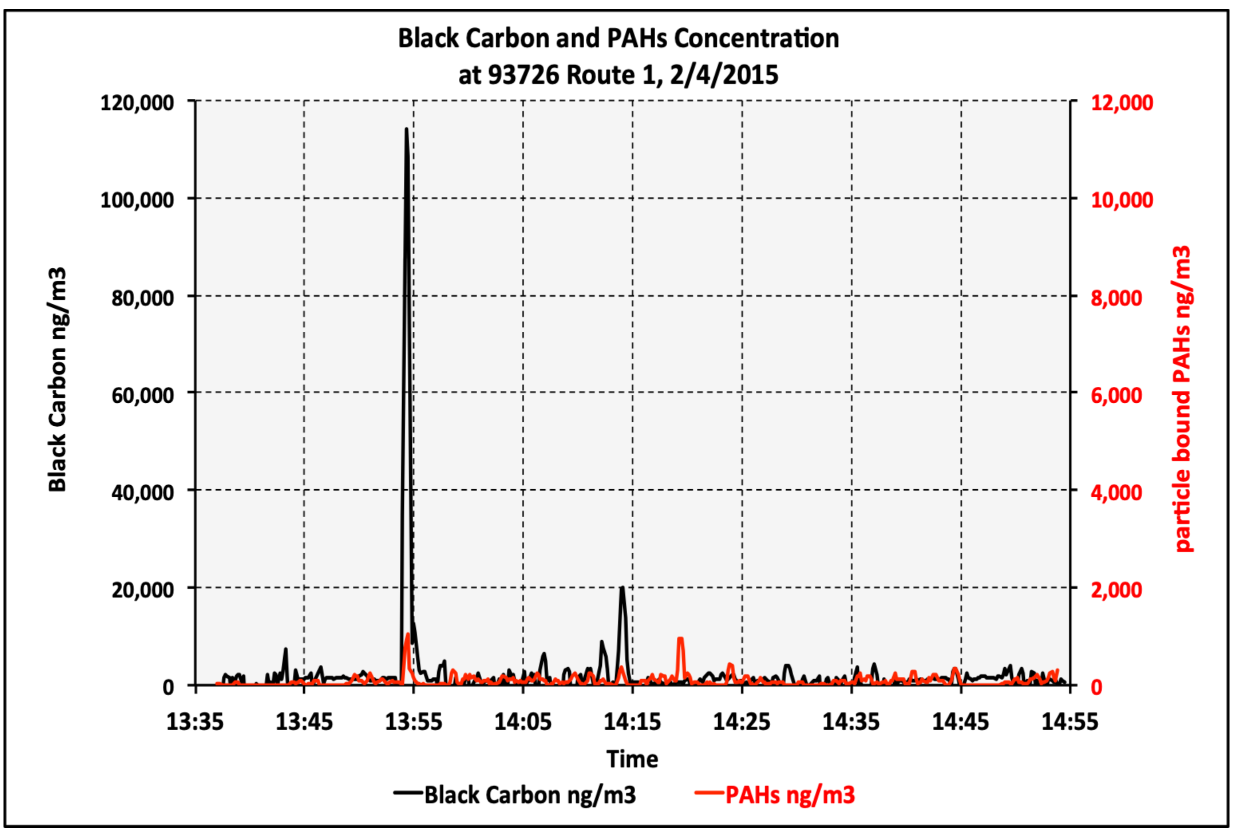


Table 2. Summary Statistics of Particle Pollutant Concentrations (Mg/M³) And the Compositional Proportion of the Particulate Matter Species

Statistics	$PM_{2.5}$	BC	PAH	$BC/PM_{2.5}$	$PAHs/PM_{2.5}$	PAHs/BC
Maximum	64.9	4.00	0.329	41.38%	5.00%	344.08%
95%	40.3	1.90	0.210	18.54%	3.07%	60.77%
75%	19.8	0.91	0.138	9.88%	1.40%	25.14%
Mean	14.9	0.78	0.104	7.52%	1.11%	22.56%
Median	11.5	0.64	0.091	5.87%	0.76%	14.61%
Geo Mean	11.1	0.62	0.089	5.55%	0.80%	14.84%
25%	6.4	0.40	0.059	3.22%	0.47%	8.44%
Minimum	1.3	0.10	0.012	0.29%	0.06%	1.65%
N	155	151	153	151	153	149

Figure 12. Time Series Plot Example for Black Carbon (BC) and Polycyclic Aromatic Hydrocarbons (Pahs) Concentrations at a Roadside Walking Route. The Huge Concentration Peaks of Black Carbon and Pahs Were Observed Near an Old Lawnmower that was Starting.



4.2 Geospatial Descriptive Analyses of Roadside Air Quality Sensor Data

The average PM2.5 concentration on routes was 3.8 times higher than PM2.5 at an indoor location. Particle concentrations were consistently higher than the concentrations measured at the ambient monitoring stations. Particle concentrations varied by the types of the roadways and immediate local sources encountered during sampling (Tables 3 and 4). PM2.5 was highest on roads over highways, while black carbons were highest on arterial roadways. The impact of sources such as passing buses, active smokers, motorcycles, and lawnmowers was greater for PM2.5, BC, and PAHs, while PAHs were also higher near schools and a factory. It is notable that black carbon and PAHs were minimal near the CNG school bus. Figures 13 and 14 illustrate the distribution of the PM2.5 and black carbon concentrations for overall walking routes respectively. The higher concentrations were observed near the highways for both PM2.5 and BC. However, the PM2.5 and BC concentrations did not align for every route. The ratios between the particle species would be useful to identify the local source profiles.

Table 3. Mean Particle Concentrations (μg/m^3) by Type of Roadways (Partial Data, 2015-2016 Data)

	$PM_{2.5}$	BC	PAHs
Arterial / Collector over Highway	13.1	0.313	0.064
Arterial / Collector	8.5	0.811	0.055
Residential Street	7.9	0.551	0.054

Table 4. Particle Concentrations and Compositional Proportions by The Immediate Local Sources (Partial Data, 2015-2016 Data)

	$PM_{2.5}$ (μg/m^3)	BC (μg/m^3)	PAHs (μg/m^3)	BC/ $PM_{2.5}$ (%)	PAH/ $PM_{2.5}$ (%)	PAH/ BC (%)
Bus – Passing	27.2	1.1	0.010	3.9	0.0	0.3
Bus stop	6.4	0.9	0.045	15.0	1.0	7.6
Crossing street	7.4	1.4	0.025	19.5	0.3	0.6
Factory	2.6	0.5	0.072	19.1	2.8	14.7
Road over Highway	13.1	0.3	0.064	1.7	0.4	61.8
Road under a highway overpass	3.4	0.3	0.059	9.9	1.8	17.7
Old lawnmower	17.8	66.4	0.049	374.0	0.3	0.1
Motorcycle	19.6	1.6	0.097	8.2	0.5	7.4
School	17.0	1.0	0.142	5.0	0.8	11.0
School Bus – CNG	17.4	0.0	0.023	0.0	0.1	0.0
Active smoker	26.2	1.2	0.091	4.4	0.3	2.9
Grand Total	8.3	0.7	0.055	9.8	0.9	16.1

Figure 13. Distribution of Average $PM_{2.5}$ ($\mu g/m^3$) for Walking Route Samples

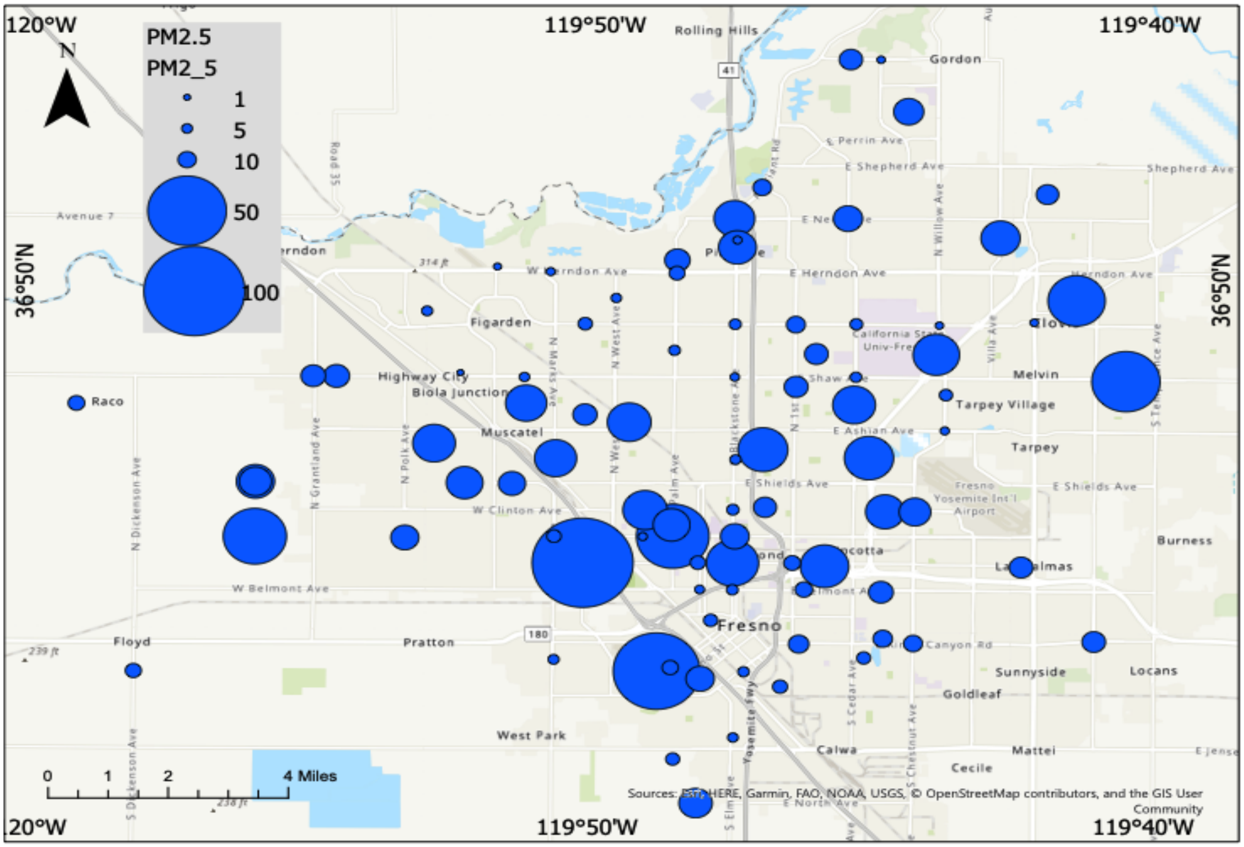
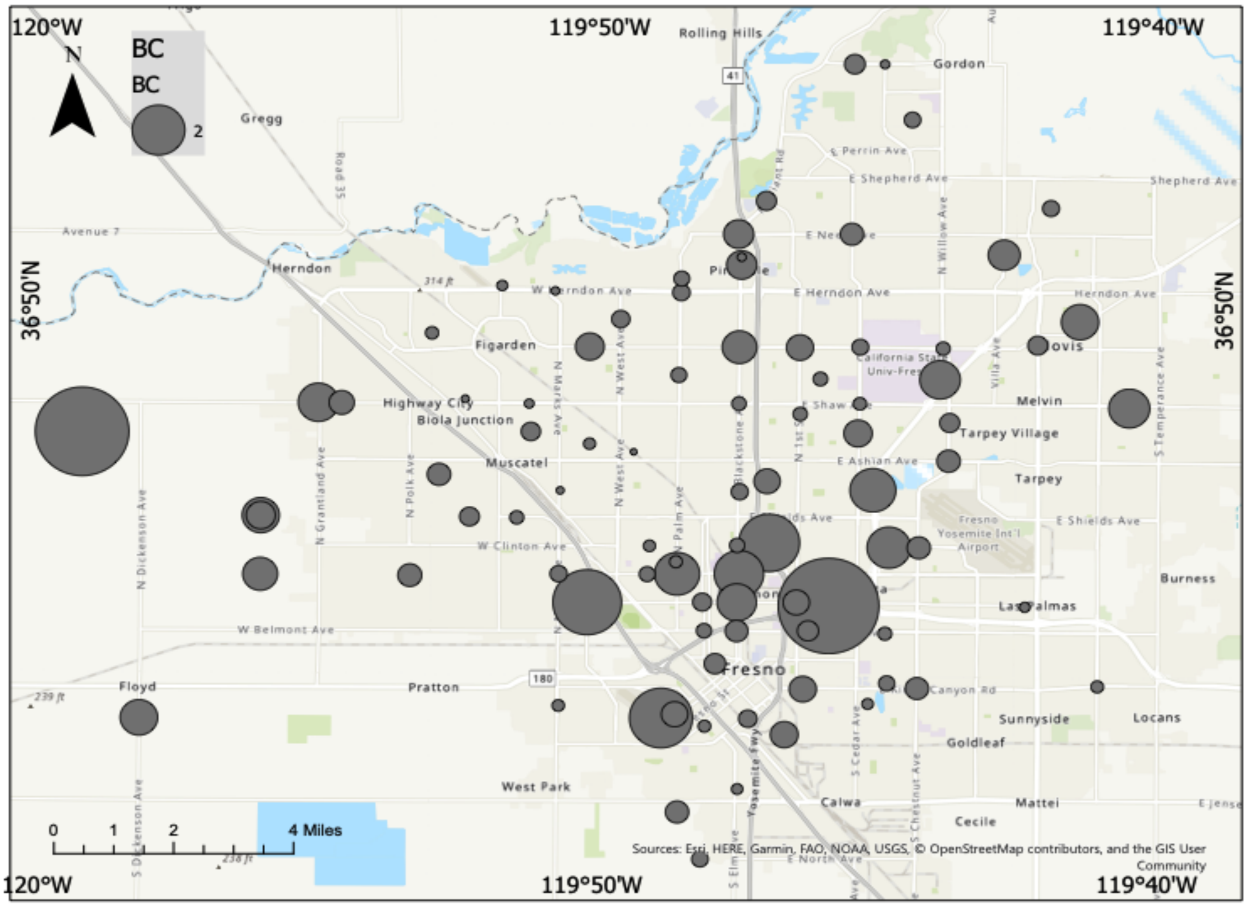


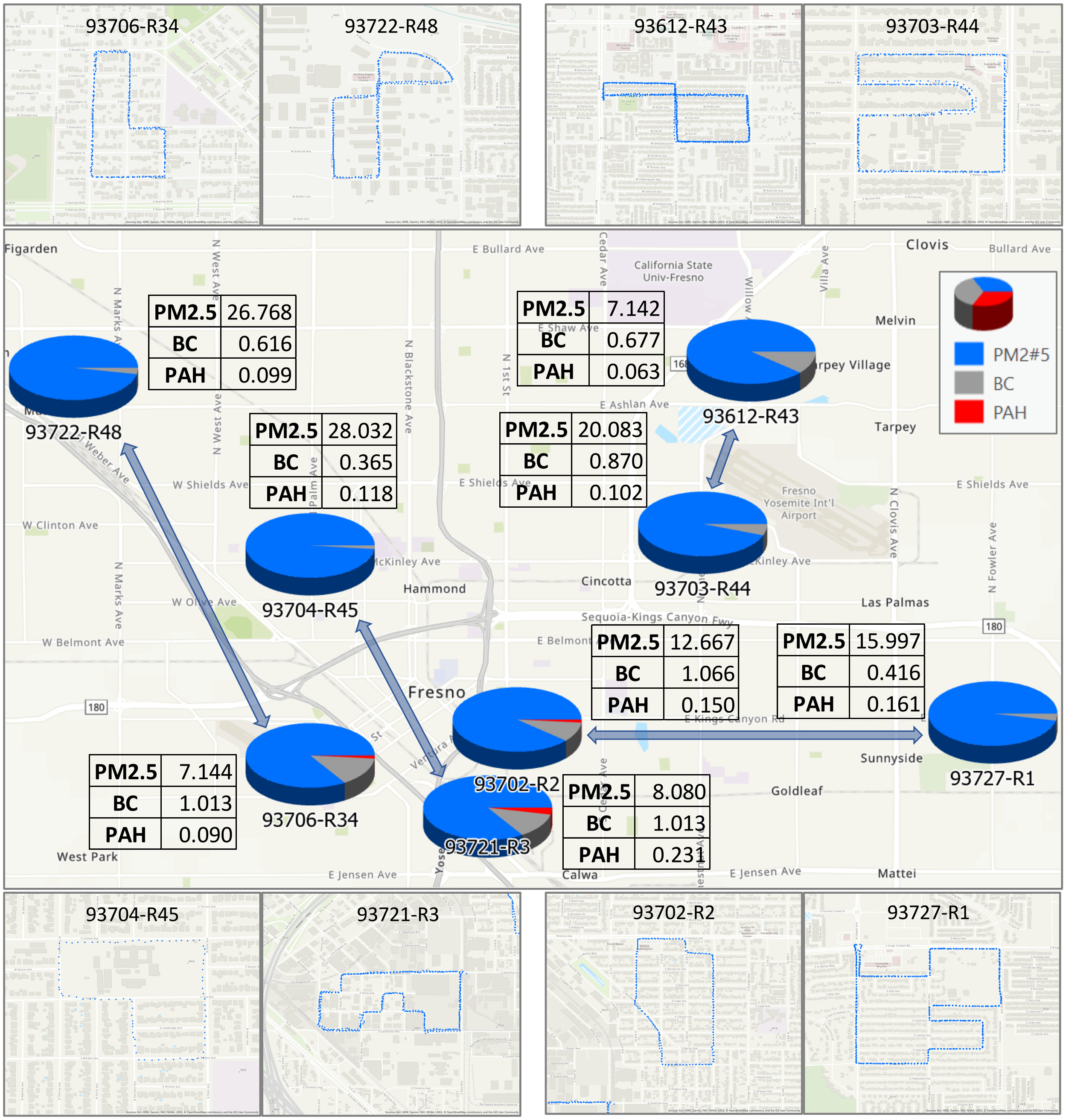
Figure 14. Distribution of Average Black Carbon (µg/m³) for Walking Route Samples



4.3 Parallel measurement data analyses

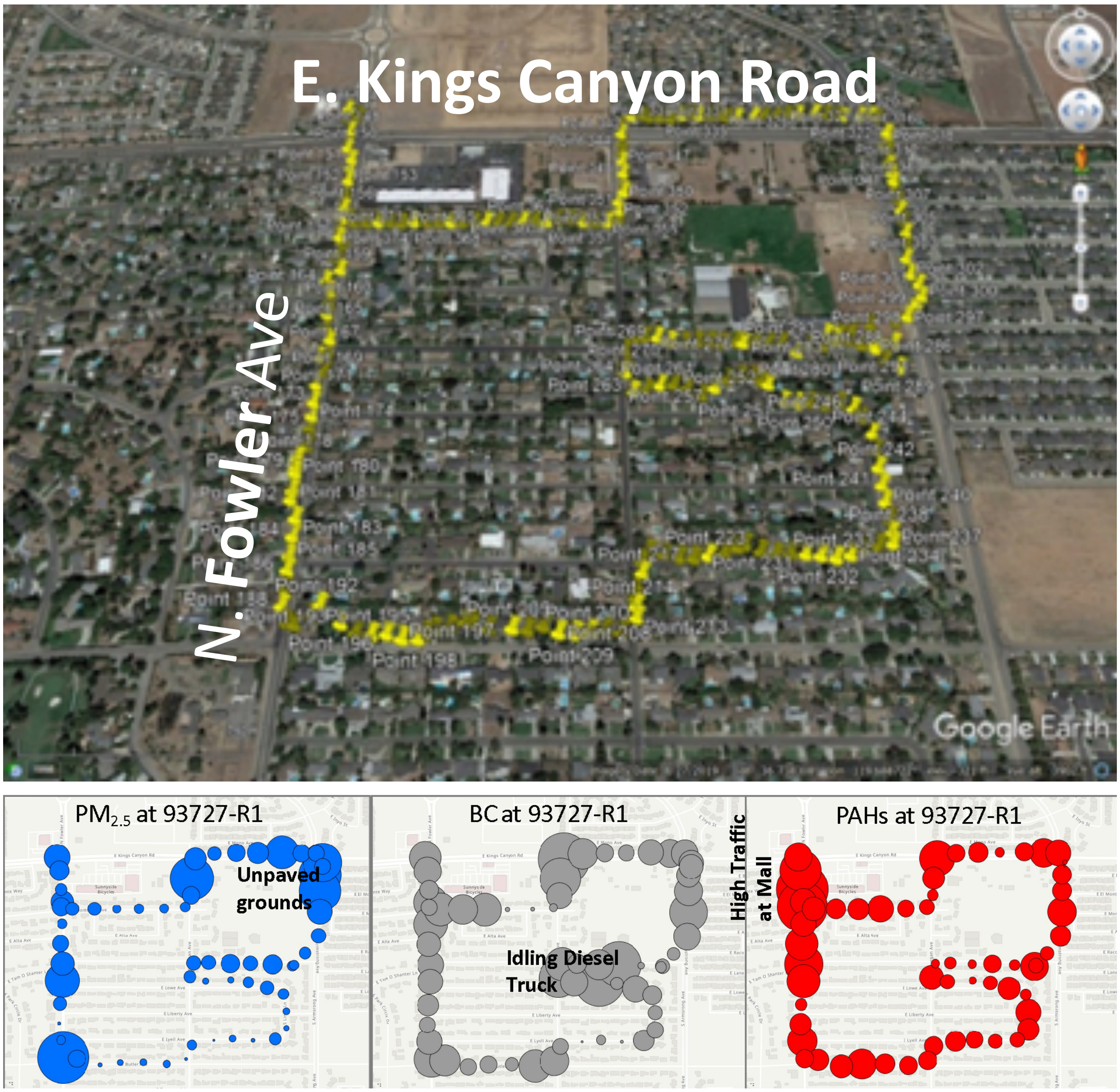
To minimize the impact of temporal variability on the particulate matter concentrations, the PM2.5, black carbon, and PAHs data from 8 walking routes were measured on the same day and time (parallel measurements). In Figure 15, the paired routes that were sampled parallelly are indicated by arrows. The GPS logged location points of the detailed routes (blue dots) illustrate each sampling location. As listed in each table, the particle compositions at the paired locations are distinctive from each other. For example, PM2.5 at 93704-R45 was more than 3 times higher than PM2.5 at 93721-R3. However, the concentrations of BC and PAHs at 93721-R3 were 2 to 3 times higher than those of 93704-R45. Similar trends of high BC and PAHs were observed at the routes near the highways (Hwy99, Hwy 41, Hwy 168) and high industrial areas (93704-R45, 93721-R3, 93702-R2, and 93612-R43). In contrast, the paired locations had elevated PM2.5, with more residential development, and unpaved grounds. It is interesting to note that the 93727-R1 had a newly built shopping mall that had a lot of traffic while 93702-R2 barely had any traffic in the early mornings.

Figure 15. The Parallel Repeated Measurements of PM2.5, Black Carbon, and Pahs At 8 Walking Routes on the Same Days and Times. The Paired Routes are Indicated by Arrows. The Values are Averages of Overall Measurements Including Repeats.



The walking route samples were immediately influenced by the crossing emissions or resuspended dust. To present the variability between different particulate matter species, PM2.5 (blue), BC (gray), and PAHs (red) concentrations and GPS waypoints measured at 93727-R1 on a sampling period are illustrated in Figure 16. For example, at 93727-R1 (one of the paired locations), elevated black carbon concentrations were observed in the middle of the residential area without any moving vehicles. PM2.5 and PAHs were not high at these locations. A pest control truck with an idling engine was the only suspicious emission source based on the sampler's observation at the location.

Figure 16. PM2.5, BC, and PAHs Concentrations and GPS Waypoints Measured at 93727-R1 on a Sampling Period.



4.4 Neighborhood Characteristic Analyses in zip codes

The assimilated GPS layers are illustrated in Figure 17. The layers overlaid are Fresno City Boundary, Road Intersection (+ speed bump), Road segment (TIGER), CHAPS walking route air quality and location data, and CalEnviroScreen scores and variables. The average of the particle pollution and CalEnviroScreen scores and variables indicating health and environments (SSO disorder and order, asthma, and low birth weight summarized by zip codes) are listed in Table 5. Diesel PM emissions were highest near zip codes close to roads such as California state route 99 and 41. Elevated levels of asthma were observed in zip codes such as 93706, 93701, & 93721.

Figure 17. Gathered GIS Layers; Fresno City Boundary, Road Intersection (+ speed bump), Road segment, Previous CHAPS data, CalEnviroScreen Data at Census Tracts

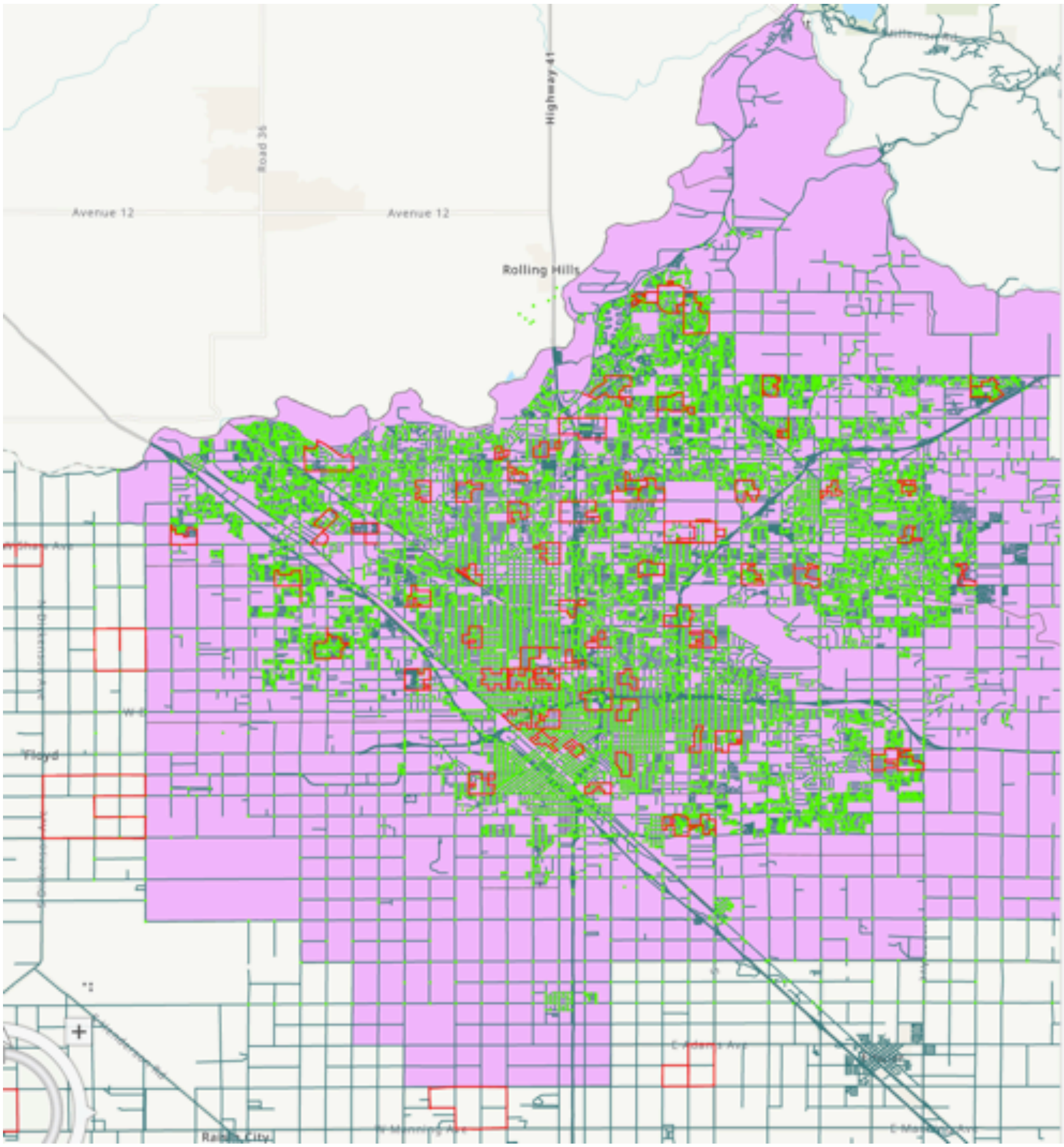


Table 5. Mean Particulates Concentration and the Secondary Neighborhoods' Environmental and Health Characteristic Indicators by Zip Codes

Zip Code	Average BC (µg/m3)	Average PM 2.5 (µg/m3)	BC/PM 2.5 (%)	Traffic (vehicle - kilometers per hour per road length)	Diesel PM Emission (kg/day)	Walk score	CES Pollution Burden Score	CES Population Characteristics Score	CES Total Score	SSO Disorder Walking	SSO Order Walking	Asthma (Rate per 10,000)	Low Birth Weight (Rate per 10,000)
93723	2.00	15.8	12.7	85	8	NA	4.5	5.2	23.4	6.9	.73	58	4.9
93701	0.71	6.4	11.1	1468	59	56.5	4.8	9.2	44.16	39.8	22.9	116	6.0
93612	0.63	6.3	10.0	556	28	34.9	6.4	6.2	39.68	3.89	6.76	63	5.0
93711	0.50	5.2	9.6	966	18	29.3	6.0	4.4	26.4	3.04	11.05	30	5.1
93710	0.65	7.9	8.2	1315	37	35.5	5.9	6.2	36.58	15.9	11.1	59	5.4
93721	0.70	8.6	8.1	1623	57	61.5	6.8	7.7	52.36	12.5	9.5	103	5.7
93703	1.50	19.7	7.6	1262	47	39.9	5.3	8.5	45.05	16.25	7	85	5.7
93702	0.77	10.9	7.1	575	26	39.9	6.6	9.1	60.06	9.4	4.7	93	5.5
93706	0.90	15.8	5.7	492	29	29.1	7.3	9.1	66.43	11.2	2.9	130	5.8
93725	1.30	24.4	5.3	696	17	14.6	7.5	7.9	59.25	12.3	3.4	69	5.2
93720	0.83	17.5	4.7	495	19	26.4	5.2	3.7	19.24	5.6	11.1	29	5.0
93726	1.09	27.0	4.0	1006	45	35.4	4.8	7.2	34.56	66.6	7.8	81	5.1
93730	0.46	11.5	4.0	329	9	NA	5.1	3.3	16.83	4.6	17.2	20	4.9
93611	1.30	34.3	3.8	339	18	20.3	5.3	3.7	19.61	2.5	5.4	36	5.2
93704	0.43	11.4	3.8	895	45	37.6	4.9	6.2	30.38	12.8	4.7	72	5.1
93722	0.53	18.3	2.9	750	22	16.3	6.4	6.9	44.16	9.7	6.6	65	5.5
93727	0.38	13.2	2.9	752	24	20.0	7.1	7.4	52.54	9.91	6.27	62	5.4
93705	0.30	19.8	1.5	739	31	36.3	4.7	8.1	38.07	17.2	4.4	88	5.3

From the correlation matrix (Figure 18), we can see that the pair (Asthma vs. CES Population Characteristics Score) has the highest positive correlation. Other pairs that have a fairly high correlation are the pairs (CES Total Score vs. CES Population Characteristics Score), (Asthma vs. CES Total Score), (Asthma vs. Low Birth Weight), (CES Population Characteristics Score vs. Low Birth Weight), (CES Pollution Burden Score vs. CES Total Score), (Walk score vs. Diesel PM Emission), and (Diesel PM Emission vs. Traffic). On the other hand, the pairs (Asthma vs. Average BC) and (BC/PM25 vs. Low Birth Weight) have a very weak correlation. The P-value table confirms that many pairs of variables have a population correlation significantly different from 0. This result confirms that there exists a significant linear relationship among many pairs of variables (Table A-2 Appendix). The statistically significant correlations at ($p<0.05$) are highlighted.

Figure 18. Correlation Matrix

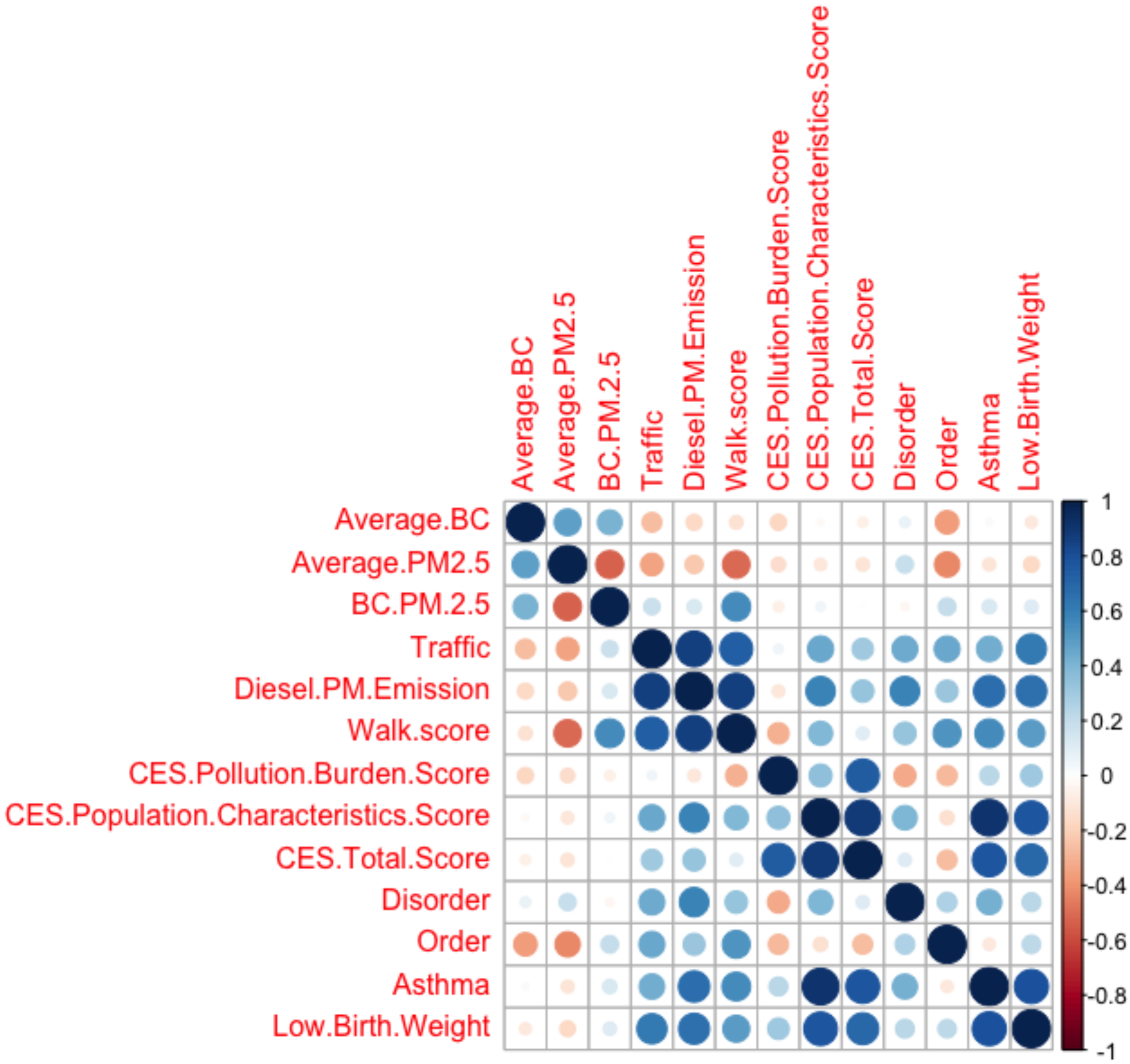
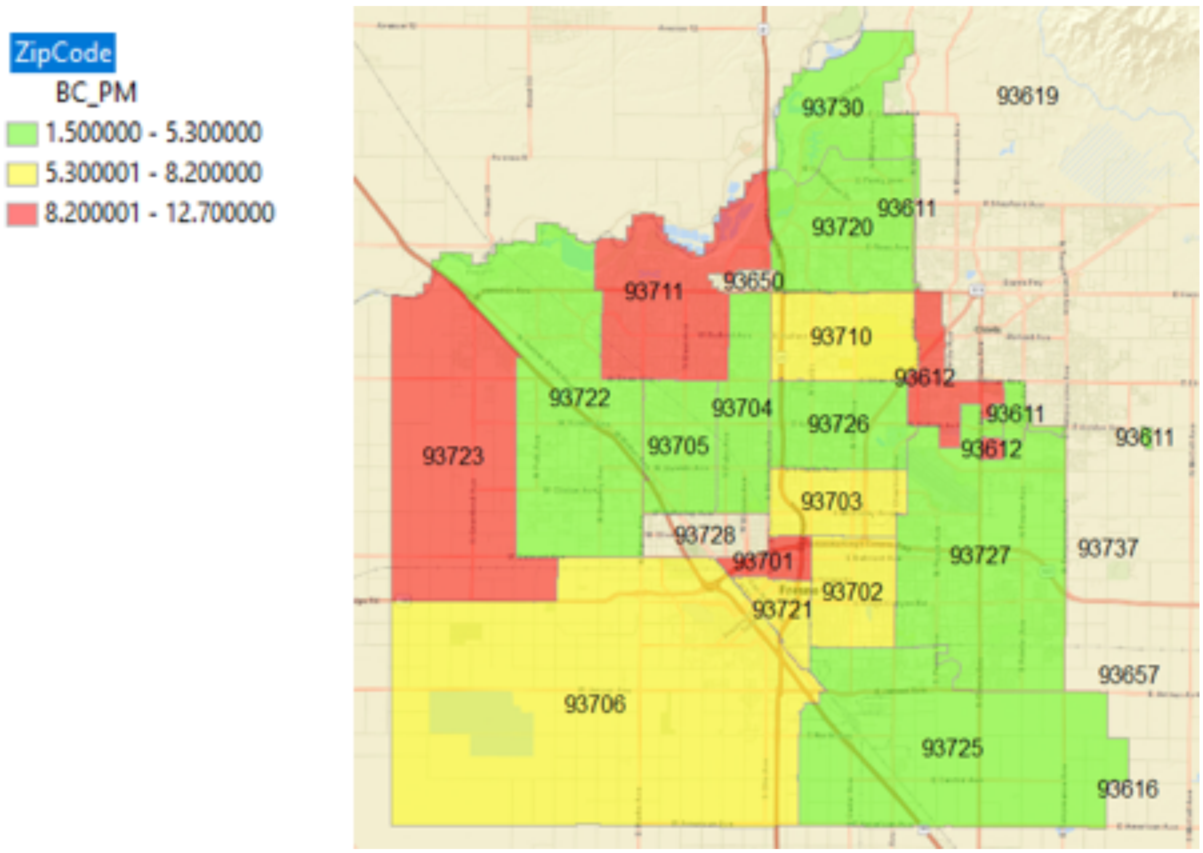


Figure 19. Map of BC/PM2.5 by Zip Code. High Level (red) of BC/PM2.5 Zip Code Areas were 93723, 93711, 93612, and 93701, Followed by Yellow Areas. The Green-colored Zip Codes Show the Lowest BC Percentages in the PM2.5.



To investigate the relationship of particulate matter near roadways and by zip code, while also taking into account spatial-temporal factors and analyzing health effects in these identified areas, data taken at routes and CalEnviroScreen indicators were analyzed. BC percent of PM2.5 is mapped in three groups in Figure 19. The highest BC percent in PM2.5 areas (red) were 93723, 93711, 93612, and 93701. The yellow areas were 93706, 93721, 90702, 93703, and 93710. Compared to the lowest (green) BC contents zip code areas, red and yellow colored zip codes areas are closer to highway 99 or contain more highway networks within the area connected to higher volume arterial roadways. These results may be due to the fact that California State Highway 99 is mainly used by diesel trucks whereas California State Route 41 & 180 traffic is primarily occupied by light-duty vehicles, a distinction which can contribute to differences in particulate matter emitted and level of black carbon measured. It is necessary to further investigate by reducing temporal and meteorological factors that influenced the short-term air quality monitoring data. Further analyses characterizing the larger particles such as fugitive dust and PM10 in relation to the land use and the unpaved and uncovered lands in the areas where the high PM2.5 levels are necessary for future study.

Previous studies have found a strong association between polycyclic aromatic hydrocarbons and rates of hospitalization and asthma near Highway 99 (Noth et al., 2011). The limitations of this research are greater variability in the zip code areas and the temporal trends of the particulate concentrations. Census tract-level examination and the standardization with particle concentrations measured at the central monitoring data would help further investigation of spatio-temporal analyses with health and built environmental indicators.

4.5 Evaluation of low-cost Sensors in Collocation Sensor calibration

The two different types of particulate monitoring air sensors (Dylos DC1700 and AtmoTube Pro) were tested for the relationship between number concentrations from low-cost sensors and mass concentrations from a more expensive and reliable DRX Dusttrak 8533 to collect particulate matters in urban air. Figures 20 and 21 illustrate the collocation measurement of three different air monitoring sensors. The side-by-side sample collection compared to the conventional methodology (DRX Dusttrack) results imply the low-cost sensors were reliable for measuring pollution levels. As shown in Figures 22 and 23, the time-series concentration increased and decreased in a similar and consistent manner by time, and the median concentrations were close. First, the sensors were calibrated at the same location in the residential setup. Second, the sensors were deployed for data collection at the selected roadside and residential locations, the central monitoring site at Clovis, and during the different modes of transportation such as on-road, in-vehicle, and on-bike riding. The sites were selected at our convenience of access rather than revisiting previously sampled routes, due to COVID-19 lockdown restrictions that affected personnel training. We plan, if possible, to continue to validate our results by revisiting the paired routes in order to compare hot spots with elevated pollution levels with relatively cleaner air quality areas. We will continue the evaluation of the sensors for a more accurate assessment of the personal exposure levels for the extended phase of the STARTRAQ study in 2021. We are developing research projects using commercially available low-cost sensors for future study.

Figure 20. Low-cost Particulate Matter Air Sensors. (Left) AtmoTube Pro. (Right) Dylos DC1700

Figure 21. Collocation Measurement (Backyard)

Figure 22. Collocation PM2.5 Mass Concentrations from Air Quality Monitor at a Residential Location from 10/30/20 to 11/05/20.

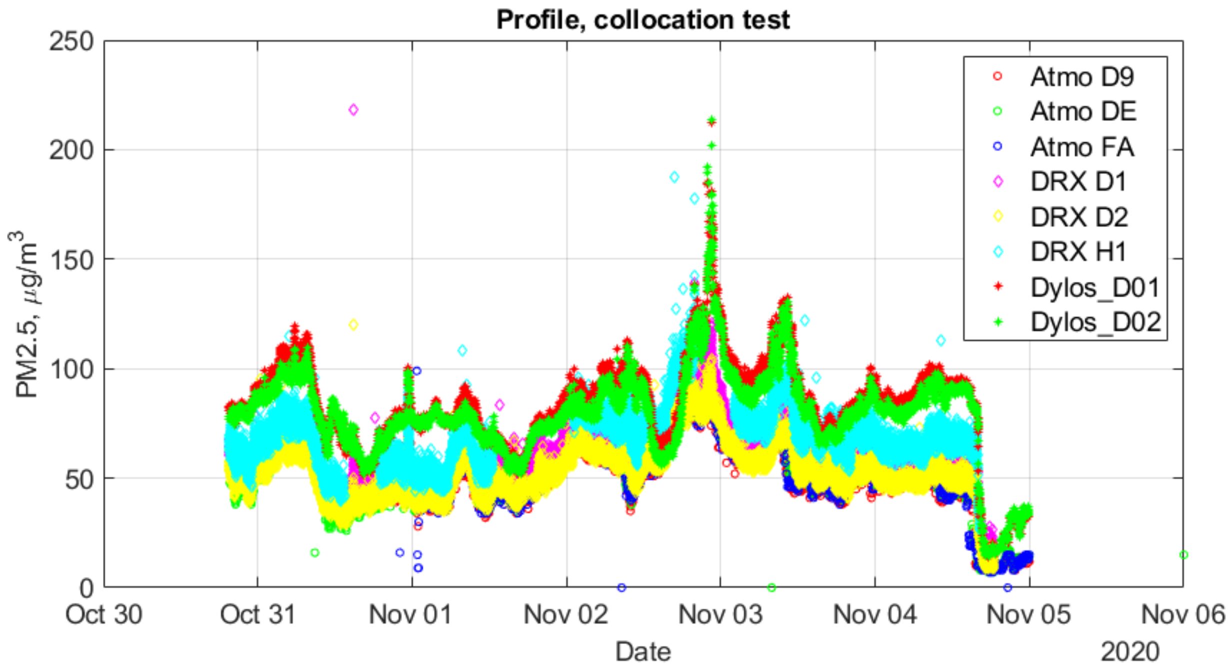


Figure 23. Box and Whisker plots of PM2.5 Mass Concentrations from Air Quality Monitors at the Residential Location from 10/30/20 to 11/05/20.

Figure 24. Inter-sensor analysis of DRX Dusttrack using PM2.5. Scatter plots of DRX Dusttrack D1 vs. DRX Dusttrack D2 (Left). Scatter plots of DRX Dusttrack D1 and H1 (Right).

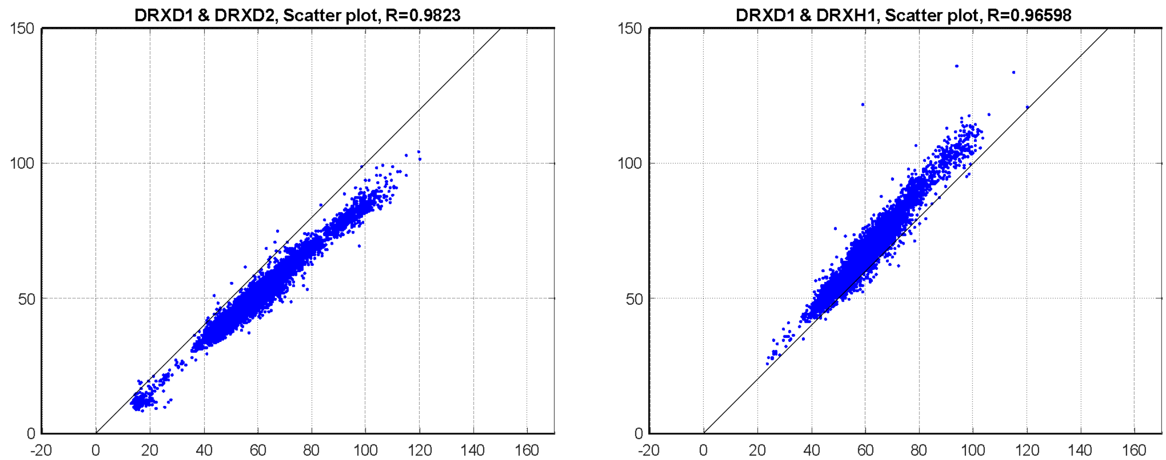


Figure 25. Inter-sensor Analysis of Dylos DC1700 Using PM2.5. Scatter Plots of Dylos DC1700 D1 vs. Dylos DC1700 D2.

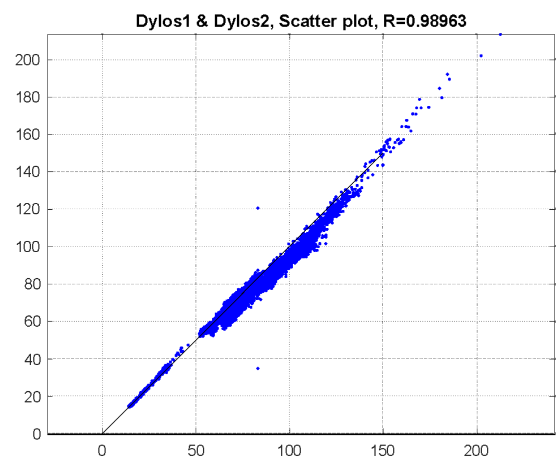


Figure 26. Inter-sensor analysis of Atmotube Pro PM2.5. Scatter plots of Atmotube Pro D9 vs. Atmotube Pro DE (Left). Atmotube Pro D9 vs. Atmotube Pro FA (Right).

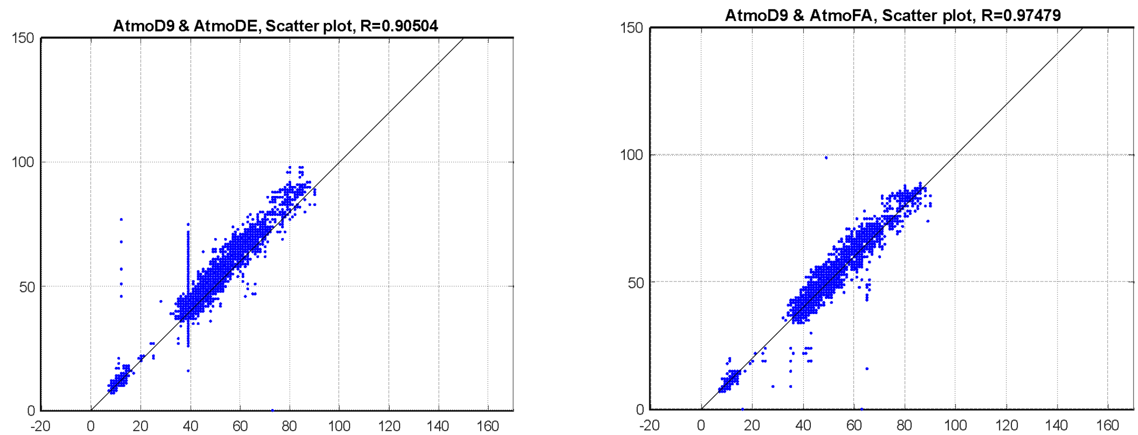


Figure 27. Scatter plots of PM2.5 Mass Concentrations from DRX Dusttracks D1 vs. Dusttracks D2 (correlation coefficient R=0.98) and H1(correlation coefficient R=0.96).

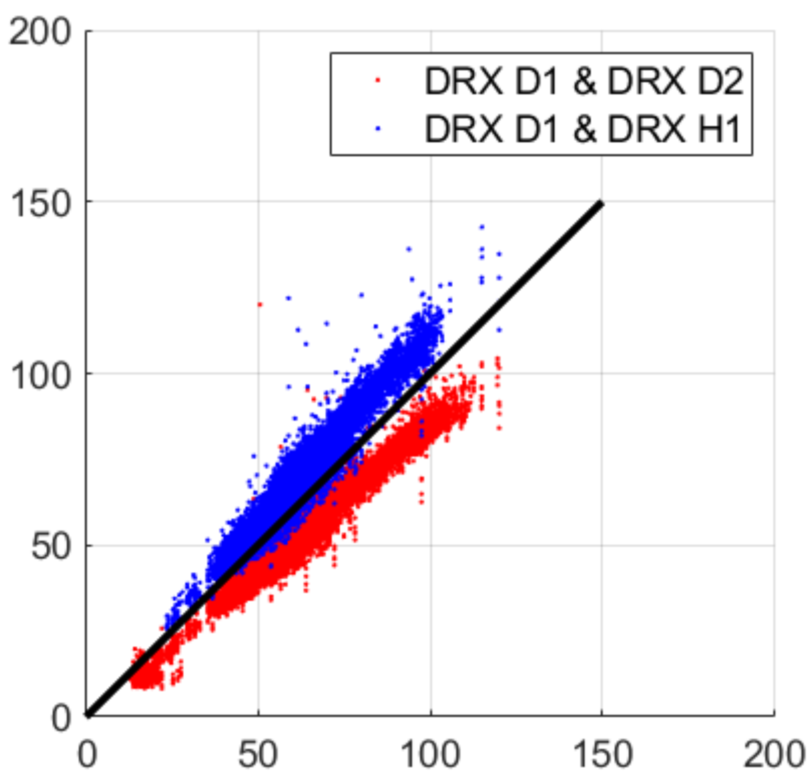


Figure 28. Intra-sensor Analysis of PM2.5. Scatter Plots of PM2.5 Mass Concentrations from DRX Dusttracks D1 vs. Dylos DC1700 Air Sensors D1 and D2 (R=0.86, R=0.83).

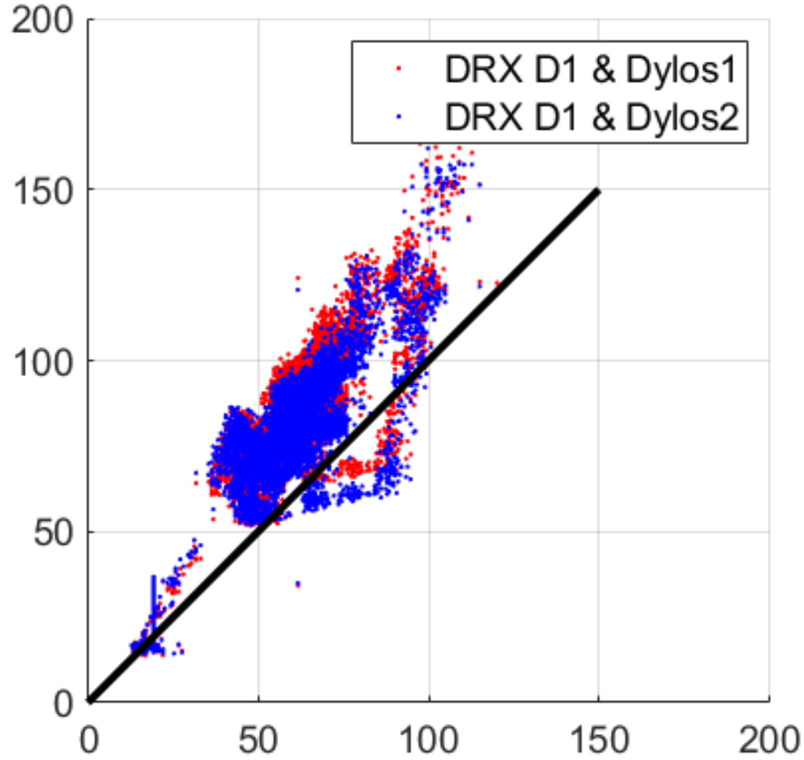
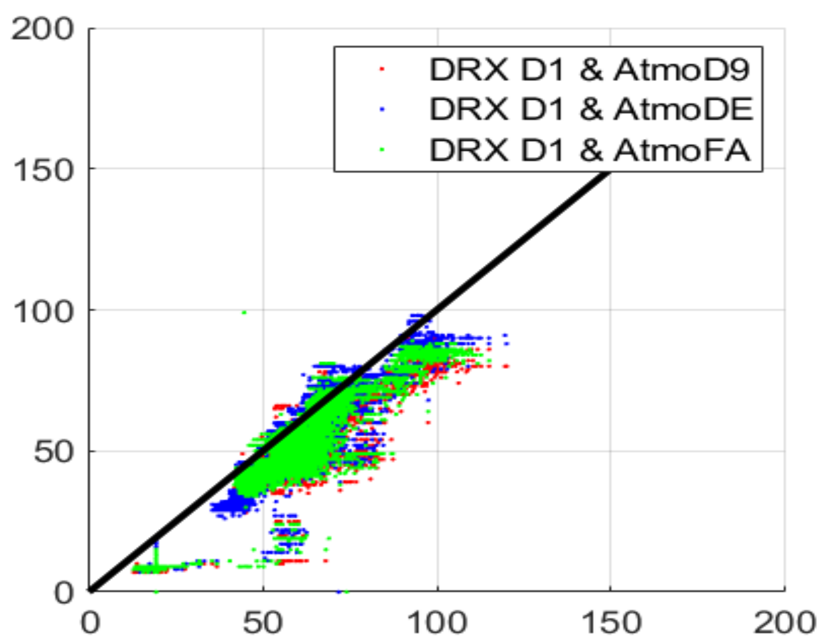


Figure 29. Scatter plots of PM2.5 Mass Concentrations from DRX Dusttracks D1 vs. Atmotube Pro Air Sensors, D9, DE, and FA (R=0.92, 0.92, 0.83 respectively).



Figures 24-26 show the correlation coefficients from inter-sensor analyses and Figures 27-29 show the correlation coefficients from intra-sensor analyses. It is evident that inter-sensor analyses provide higher correlation coefficients than intra-sensor analyses.

4.6 Spatio-Temporal Analysis of Roadside Air Quality

Time series analysis attempts to model the future in terms of previously observed values, and it has often been used to examine air pollution data. The particulate matters such as PM10, PM2.5, PM1, black carbon (BC), ultrafine particles, and polycyclic aromatic hydrocarbons (PAHs) are time-series data, and hence understanding the time dependency is crucial for this project. However, due to incomplete and missing observations, time series analysis was limited in this project.

Some initial investigations suggest that simple models are sufficient for data. The data in Figure 6 and related data were fitted into the linear models given by

$$y_{PM,t} = \alpha + \beta_1 x_{year,t} + \beta_2 w_{lon,t} + \beta_2 w_{lat,t} + \beta_3 r_{2t} + \beta_4 r_{3t} + \beta_4 r_{3t} + \beta_6 z_t + e_t \text{ (PM Model)},$$

and

$$y_{BC,t} = \alpha + \beta_1 x_{year,t} + \beta_2 w_{lon,t} + \beta_2 w_{lat,t} + \beta_3 r_{2t} + \beta_4 r_{3t} + \beta_4 r_{3t} + \beta_6 z_t + e_t \text{ (BC Model)}.$$

where α is the intercept, $x_{year,t}$ is 1 if the year is 2017 and 0 if the year is 2015, $w_{lon,t}$ is the longitude, $w_{lat,t}$ is the latitude, $r_{2t}$is 1 if the route is 2, $r_{3t}$is 1 if the route is 3, $r_{3t}$is 1 if the route is 4 and 0 if the route is 1, z_t is 1 if the zip code is 93726 and 0 if the zip code is 93706.

are assumed to follow N(0, σ^2). $y_{PM,t}$ and is the PM2.5 and black carbon (BC) measured at a minute level. Hence, these models render information about the spatio-temporal aspect of the data.

Table 6. Output from PM Model

	Estimate	Std. Error	t value	P-value
Intercept	-297.47547	39.92625	-7.451	3.33e-13 ***
Year2017	0.36606	0.04598	7.961	8.83e-15 ***
Longitude	-1.60168	0.19278	-8.309	6.69e-16 ***
Latitude	2.85952	0.48682	5.874	7.12e-09 ***
Route2	0.31003	0.02392	12.959	< 2e-16 ***
Route3	0.55878	0.07562	7.389	5.07e-13 ***
Route4	0.46067	0.04730	9.739	< 2e-16 ***
Zipcode93726	0.57826	0.05111	11.315	< 2e-16 ***

Table 7. Output from BC Model

	Estimate	Std. Error	t value	P-value
Intercept	-1087417.0	329660.6	-3.299	0.00104 **
Year2017	1662.0	729.2	2.279	0.02305 *
Longitude	-4695.2	2436.5	-1.927	0.05451
Latitude	14240.0	3605.1	3.950	7.12e-09 ***
Route2	1084.9	261.5	4.150	8.87e-05 ***
Route3	2162.2	521.8	4.143	3.88e-05 ***
Route4	1746.3	408.8	4.272	3.98e-05 ***
Zipcode93726	2720.3	369.7	7.358	7.08e-13 ***

Tables 6 and 7 show that all the variables are highly significant in both models. R2 values were 0.4765 and 0.3028 for PM and BC models, respectively.

CONCLUSIONS

- Geo-coded pollution data enhances the ability to observe spatial variations of pollutants.
- Roadside concentrations of PM2.5, black carbons, and PAHs were significantly elevated compared to the concentrations at the ambient monitoring stations because of the immediate source proximity to the emission sources and because roadside readings were collected at the ground level.
- Persistent spatial patterns of higher concentrations of black carbon and PAHs as components of PM2.5 are evident from the parallel sampling comparisons.
- The elevated PM2.5 concentrations occur near roadways with a higher volume of traffic and regions with more unpaved areas.
- The elevated black carbon concentrations occur near highway corridors, and regions with high diesel traffic/high industry.
- From the correlation between the pollution, environmental variables, and health variables, we can see that the pair (Asthma vs. CES Population Characteristics Score) has the highest positive correlation.
- Other pairs that have a fairly high correlation are the pairs (CES Total Score vs. CES Population Characteristics Score), (Asthma vs. CES Total Score), (Asthma vs. Low Birth Weight), (CES Population Characteristics Score vs. Low Birth Weight), (CES Pollution Burden Score vs. CES Total Score), (Walk score vs. Diesel PM Emission), and (Diesel PM Emission vs. Traffic).
- The collocation test showed a high degree of agreement between inter-sensors whose correlation coefficients range 0.90 - 0.98. Variability of different sensors – DRX, Dylos, and AtmoTube – showed less correlation, suggesting that calibration of those sensors is required for pollution-sensitive regions, such as temporal or human-induced activities.

Appendix A

Table A-1. The Average of Particulate Matter Species and the Coordinates of the Trailhead of Routes

ID	zip	Repeat	Date	Latitude	Longitude	PM2.5	BC	PAHs	BC/ PM2.5	PAHs/ PM2.5	PAHs/ BC
B1-93702-R1	93702	1st	2/5/2015	36.751	-119.769	11.9	NA	0.043	NA	0.36%	NA
B1-93702-R2	93702	1st	2/12/2015	36.736	-119.771	13.8	0.70	0.082	5%	0.59%	11.73%
B1-93702-R3	93702	1st	2/12/2015	36.737	-119.745	16.9	0.71	0.078	4%	0.46%	11.05%
B1-93722-R1	93722	1st	2/28/2015	36.838	-119.862	1.4	0.31	0.061	22%	4.35%	19.50%
B1-93722-R2	93722	1st	2/28/2015	36.809	-119.873	1.3	0.10	0.042	8%	3.18%	42.19%
B1-93722-R3	93722	1st	2/19/2015	36.790	-119.881	42.3	0.91	0.076	2%	0.18%	8.30%
B1-93722-R4	93722	1st	2/19/2015	36.779	-119.871	36.1	NA	0.078	NA	0.22%	NA
B1-93726-R1	93726	1st	1/30/2015	36.787	-119.750	41.4	1.26	0.041	3%	0.10%	3.25%
B1-93726-R2	93726	1st	2/3/2015	36.789	-119.782	51.7	1.65	0.033	3%	0.06%	1.98%
B1-93702-R1	93702	2nd	5/31/2015	36.751	-119.769	7.0	0.70	0.059	10%	0.85%	8.44%
B1-93726-R3	93726	1st	1/29/2015	36.801	-119.755	29.5	1.20	0.041	4%	0.14%	3.43%
B1-93702-R2	93702	2nd	5/31/2015	36.736	-119.771	6.5	0.51	0.063	8%	0.96%	12.35%
B1-93702-R3	93702	2nd	5/31/2015	36.737	-119.745	4.5	0.26	0.055	6%	1.23%	21.33%
B1-93722-R1	93722	2nd	6/1/2015	36.838	-119.862	5.0	0.23	0.056	5%	1.13%	24.71%
B1-93722-R2	93722	2nd	6/1/2015	36.809	-119.873	3.5	0.21	0.046	6%	1.32%	22.46%
B1-93722-R3	93722	2nd	3/29/2015	36.790	-119.881	10.1	0.68	0.045	7%	0.45%	6.71%
B1-93722-R4	93722	2nd	3/29/2015	36.779	-119.871	8.3	0.64	0.052	8%	0.63%	8.15%
B1-93726-R1	93726	2nd	2/4/2015	36.787	-119.750	19.6	2.17	0.093	11%	0.48%	4.29%
B1-93726-R2	93726	2nd	2/5/2015	36.789	-119.782	9.9	0.16	0.036	2%	0.36%	22.20%
B1-93726-R3	93726	2nd	2/4/2015	36.801	-119.755	23.0	0.80	0.101	3%	0.44%	12.67%
B2-93701-R1	93701	1st	6/2/2015	36.750	-119.791	2.4	0.41	0.046	17%	1.88%	11.10%
B2-93701-R2	93701	1st	3/26/2015	36.758	-119.773	3.2	0.73	0.012	23%	0.38%	1.65%
B2-93701-R3	93701	1st	4/11/2015	36.750	-119.800	6.1	0.47	0.033	8%	0.54%	7.01%
B2-93704-R1	93704	1st	4/3/2015	36.837	-119.808	13.0	0.67	0.046	5%	0.35%	6.80%
B2-93704-R2	93704	1st	5/29/2015	36.816	-119.809	5.8	0.43	0.046	7%	0.79%	10.63%
B2-93704-R3	93704	1st	4/6/2015	36.809	-119.790	2.4	0.24	0.034	10%	1.39%	14.19%
B2-93704-R4	93704	1st	5/29/2015	36.772	-119.791	5.2	0.50	0.035	10%	0.67%	7.04%
B2-93728-R1	93728	1st	4/10/2015	36.765	-119.844	6.8	NA	0.035	NA	0.51%	NA
B2-93728-R2	93728	1st	6/3/2015	36.765	-119.818	3.3	0.51	0.037	15%	1.12%	7.32%
B2-93728-R3	93728	1st	4/9/2015	36.758	-119.801	12.8	0.78	0.024	6%	0.19%	3.06%
B2-93701-R1	93701	2nd	6/8/2015	36.750	-119.791	8.9	1.12	0.050	13%	0.56%	4.47%
B2-93701-R2	93701	2nd	6/8/2015	36.758	-119.773	15.0	1.10	0.055	7%	0.37%	5.02%
B2-93701-R3	93701	2nd	6/2/2015	36.750	-119.800	2.7	0.43	0.056	16%	2.06%	13.21%
B2-93704-R1	93704	2nd	6/5/2015	36.837	-119.808	3.7	0.41	0.074	11%	2.02%	18.09%
B2-93704-R2	93704	2nd	6/5/2015	36.816	-119.809	5.2	0.52	0.083	10%	1.60%	16.11%
B2-93704-R3	93704	2nd	6/7/2015	36.809	-119.790	5.8	0.60	0.036	10%	0.62%	6.07%
B2-93704-R4	93704	2nd	6/7/2015	36.772	-119.791	6.9	0.40	0.051	6%	0.75%	12.79%
B2-93728-R1	93728	2nd	6/4/2015	36.765	-119.844	8.1	0.53	0.058	7%	0.72%	10.94%
B2-93728-R2	93728	2nd	6/4/2015	36.765	-119.818	4.6	0.45	0.064	10%	1.41%	14.31%

ID	zip	Repeat	Date	Latitude	Longitude	PM2.5	BC	PAHs	BC/ PM2.5	PAHs/ PM2.5	PAHs/ BC
B2-93728-R3	93728	2nd	6/3/2015	36.758	-119.801	3.3	0.43	0.041	13%	1.24%	9.61%
B3-93710-R1	93710	1st	4/4/2016	36.823	-119.754	6.3	0.51	0.225	8%	3.55%	43.85%
B3-93710-R2	93710	1st	4/4/2016	36.823	-119.790	5.8	1.25	0.242	22%	4.16%	19.33%
B3-93710-R3	93710	1st	4/4/2016	36.809	-119.754	7.4	0.36	0.219	5%	2.94%	61.18%
B3-93710-R4	93710	1st	4/5/2016	36.823	-119.772	10.4	0.94	0.250	9%	2.40%	26.46%
B3-93720-R1	93720	1st	4/5/2016	36.860	-119.783	10.2	0.65	0.283	6%	2.78%	43.73%
B3-93720-R2	93720	1st	4/5/2016	36.852	-119.757	17.3	0.78	0.195	5%	1.13%	24.85%
B3-93720-R3	93720	1st	4/6/2016	36.852	-119.791	24.9	1.07	0.189	4%	0.76%	17.62%
B3-93728-R1	93728	1st	4/7/2016	36.757	-119.836	64.9	2.66	0.206	4%	0.32%	7.74%
B3-93728-R2	93728	1st	4/7/2016	36.765	-119.809	46.0	1.68	0.192	4%	0.42%	11.42%
B3-93728-R3	93728	1st	4/7/2016	36.758	-119.791	32.5	1.45	0.100	4%	0.31%	6.93%
B3-93730-R1	93730	1st	4/6/2016	36.881	-119.739	17.8	0.51	0.206	3%	1.15%	40.68%
B3-93730-R2	93730	1st	4/6/2016	36.896	-119.756	13.3	0.68	0.138	5%	1.03%	20.30%
B3-93730-R3	93730	1st	4/15/2016	36.896	-119.747	3.4	0.21	0.172	6%	5.00%	83.33%
B3-93710-R3	93710	2nd	4/15/2016	36.809	-119.754	3.7	0.39	0.179	11%	4.80%	45.55%
B4-93612-R1	93612	1st	6/17/2016	36.823	-119.729	3.4	0.40	0.097	12%	2.85%	24.36%
B4-93612-R2	93612	1st	6/17/2016	36.824	-119.701	3.6	0.64	0.106	18%	3.00%	16.53%
B4-93612-R3	93612	1st	6/17/2016	36.794	-119.727	3.9	0.79	0.109	20%	2.78%	13.79%
B4-93727-R1	93727	1st	3/15/2016	36.737	-119.682	7.2	0.19	0.097	3%	1.36%	52.57%
B1-93702-R2	93702	4th	5/26/2016	36.736	-119.771	7.8	1.19	0.174	15%	2.24%	14.61%
B1-93702-R2	93702	5th	5/27/2016	36.736	-119.771	10.6	0.94	0.148	9%	1.40%	15.80%
B1-93702-R2	93702	6th	6/2/2016	36.736	-119.771	9.1	1.29	0.109	14%	1.19%	8.43%
B1-93702-R2	93702	7th	6/2/2016	36.736	-119.771	12.4	0.98	0.061	8%	0.49%	6.18%
B1-93702-R2	93702	8th	6/3/2016	36.736	-119.771	12.3	1.11	0.221	9%	1.79%	19.95%
B1-93702-R2	93702	9th	6/3/2016	36.736	-119.771	19.0	0.88	0.210	5%	1.11%	23.87%
B4-93727-R1	93727	3rd	5/26/2016	36.737	-119.682	7.1	0.26	0.153	4%	2.15%	58.06%
B4-93727-R1	93727	4th	5/27/2016	36.737	-119.682	13.5	0.31	0.171	2%	1.27%	55.56%
B4-93727-R1	93727	5th	6/2/2016	36.737	-119.682	11.5	0.22	0.185	2%	1.60%	82.61%
B4-93727-R1	93727	6th	6/2/2016	36.737	-119.682	13.3	0.34	0.211	3%	1.59%	61.68%
B4-93727-R1	93727	7th	6/3/2016	36.737	-119.682	19.0	0.64	0.131	3%	0.69%	20.54%
B4-93727-R1	93727	8th	6/3/2016	36.737	-119.682	23.0	0.46	0.118	2%	0.51%	25.41%
B4-93727-R3	93727	1st	3/15/2016	36.736	-119.736	10.4	0.78	0.086	8%	0.84%	11.05%
B4-93711-R1	93711	1st	6/16/2016	36.823	-119.835	7.3	1.01	0.141	14%	1.92%	13.93%
B4-93711-R2	93711	1st	6/16/2016	36.830	-119.826	4.8	0.58	0.134	12%	2.80%	23.03%
B4-93711-R3	93711	1st	6/16/2016	36.808	-119.854	4.8	0.22	0.061	5%	1.27%	27.26%
B5-93706-R1	93706	2nd	5/30/2017	36.727	-119.97	8.4	1.9	0.078	23%	0.93%	4.08%
B5-93706-R1	93706	1st	5/26/2017	36.727	-119.97	8.64	0.8	0.081	10%	0.94%	9.81%
B5-93706-R2	93706	1st	3/10/2017	36.728	-119.8131	55.3	2.4	0.061	4%	0.11%	2.53%
B5-93706-R3	93706	1st	5/30/2017	36.619	-119.826	28.5	0.3	0.203	1%	0.71%	60.15%
B5-93706-R4	93706	1st	5/30/2017	36.618	-120.002	53.8	0.5	0.197	1%	0.37%	38.37%
B5-93721-R1	93721	1st	5/25/2017	36.742	-119.797	7.2	0.7	NA	10%	NA	NA
B5-93721-R2	93721	1st	5/27/2017	36.47	-119.5	19.5	0.1	0.195	0%	1.00%	344.08%
B5-93721-R2	93721	2nd	6/5/2017	36.47	-119.5	5.4	0.7	NA	13%	NA	NA
B5-93721-R3	93721	1st	5/26/2017	36.724	-119.776	7.1	0.8	0.112	12%	1.58%	13.15%
B5-93721-R3	93721	2nd	6/13/2017	36.724	-119.776	8.3	1.6	0.329	19%	3.96%	20.90%

ID	zip	Repeat	Date	Latitude	Longitude	PM2.5	BC	PAHs	BC/ PM2.5	PAHs/ PM2.5	PAHs/ BC
B5-93721-R3	93721	3rd	6/13/2017	36.724	-119.776	8.9	0.9	0.166	10%	1.86%	18.90%
B5-93721-R3	93721	4th	6/13/2017	36.724	-119.776	7.0	0.6	0.199	8%	2.84%	34.09%
B5-93721-R4	93721	1st	5/26/2017	36.728	-119.787	5.5	0.6	0.079	11%	1.44%	13.66%
B5-93650-R1	93650	1st	3/18/2017	36.844	-119.79	23.0	1.1	0.057	5%	0.25%	5.32%
B5-93650-R2	93650	3rd	6/5/2017	36.8404	-119.808	14.7	0.5	0.103	3%	0.70%	21.72%
B5-93611-R1	93611	1st	3/17/2017	36.847	-119.711	23.9	1.1	0.059	5%	0.25%	5.18%
B5-93611-R2	93611	1st	3/17/2017	36.808	-119.673	43.2	1.5	0.059	4%	0.14%	3.89%
B5-93611-R3	93611	1st	3/17/2017	36.83	-119.688	35.9	1.4	0.055	4%	0.15%	4.03%
B5-93703-R1	93703	1st	3/17/2017	36.773	-119.781	13.1	2.3	0.087	18%	0.66%	3.73%
B5-93703-R2	93703	1st	3/17/2017	36.765	-119.79	16.9	1.9	0.109	11%	0.65%	5.87%
B5-93703-R3	93703	1st	3/18/2017	36.757	-119.763	30.0	4.0	0.139	13%	0.46%	3.48%
B5-93703-R4	93703	1st	3/18/2017	36.772	-119.745	23.5	1.6	0.168	7%	0.71%	10.32%
B5-93705-R1	93705	1st	5/25/2017	36.796	-119.822	26.9	0.1	0.118	0%	0.44%	117.88%
B5-93705-R2	93705	1st	5/25/2017	36.772	-119.817	27.3	0.3	0.170	1%	0.62%	52.11%
B5-93705-R3	93705	1st	5/25/2017	36.786	-119.844	25.7	0.2	0.110	1%	0.43%	72.60%
B5-93723-R1	93723	1st	5/23/2017	36.808	-119.91	15.1	0.9	0.138	6%	0.91%	15.88%
B5-93723-R2	93723	1st	5/23/2017	36.779	-119.934	23.3	1.4	0.176	6%	0.76%	12.95%
B5-93723-R3	93723	1st	5/25/2017	36.8	-119.988	8.9	3.7	0.092	41%	1.04%	2.50%
B5-93725-R1	93725	1st	5/23/2017	36.808	-119.917	14.2	1.5	0.088	11%	0.62%	5.85%
B5-93725-R2	93725	1st	5/23/2017	36.779	-119.934	19.3	1.0	0.130	5%	0.67%	12.71%
B5-93725-R3	93725	1st	5/23/2017	36.764	-119.934	39.8	1.3	0.154	3%	0.39%	12.14%
B5-93740-R1	93740	1st	3/18/2017	36.815	-119.73	28.7	1.5	0.140	5%	0.49%	9.33%
B6-93706-R34	93706	1st	5/26/2017	36.729	-119.809	17.4	0.3	0.119	2%	0.68%	34.48%
B6-93706-R34	93706	2nd	6/8/2017	36.729	-119.809	6.0	0.6	0.050	10%	0.83%	8.57%
B6-93706-R34	93706	3rd	6/8/2017	36.729	-119.809	6.5	2.4	0.062	37%	0.95%	2.55%
B6-93706-R34	93706	4th	6/8/2017	36.729	-119.809	6.0	0.6	0.063	10%	1.05%	10.82%
B6-93706-R34	93706	5th	6/15/2017	36.729	-119.809	7.6	0.9	0.092	12%	1.22%	10.04%
B6-93706-R34	93706	6th	6/15/2017	36.729	-119.809	9.0	0.9	0.151	9%	1.67%	17.72%
B6-93706-R34	93706	7th	6/15/2017	36.729	-119.809	7.7	0.7	0.120	9%	1.55%	16.81%
B6-93706-R35	93706	1st	5/26/2017	36.726	-119.8	16.8	0.3	0.091	2%	0.54%	26.49%
B6-93706-R36	93706	1st	6/5/2017	36.704	-119.808	7.2	0.8	0.060	11%	0.84%	7.63%
B6-93706-R37	93706	1st	5/26/2017	36.692	-119.801	20.0	0.5	0.128	3%	0.64%	25.34%
B6-93706-R38	93706	1st	5/31/2017	36.71	-119.79	4.9	0.3	0.074	6%	1.52%	25.73%
B6-93706-R39	93706	1st	5/31/2017	36.731	-119.844	5.2	0.3	0.033	6%	0.63%	10.01%
B6-93702-R40	93702	1st	5/30/2017	36.732	-119.751	7.1	0.3	0.108	4%	1.52%	36.64%
B6-93702-R41	93702	1st	5/31/2017	36.75	-119.746	14.2	0.4	0.105	3%	0.74%	26.66%
B6-93727-R42	93727	1st	5/31/2017	36.757	-119.704	13.6	0.3	0.116	2%	0.85%	44.69%
B6-93612-R43	93612	1st	6/2/2017	36.804	-119.727	3.8	0.5	0.059	14%	1.56%	11.38%
B6-93612-R43	93612	2nd	6/7/2017	36.804	-119.727	6.9	0.7	0.046	11%	0.66%	6.27%
B6-93612-R43	93612	3rd	6/7/2017	36.804	-119.727	6.9	0.6	0.057	8%	0.83%	9.75%
B6-93612-R43	93612	4th	6/7/2017	36.804	-119.727	6.7	0.6	0.080	9%	1.18%	12.77%
B6-93612-R43	93612	5th	6/7/2017	36.804	-119.727	7.4	0.7	0.059	10%	0.79%	8.31%
B6-93612-R43	93612	6th	6/7/2017	36.804	-119.727	7.8	0.7	0.074	10%	0.95%	9.97%
B6-93703-R44	93703	1st	5/31/2017	36.772	-119.736	13.4	0.4	0.086	3%	0.64%	23.06%
B6-93703-R44	93703	2nd	6/7/2017	36.772	-119.736	17.0	0.7	0.073	4%	0.43%	10.80%

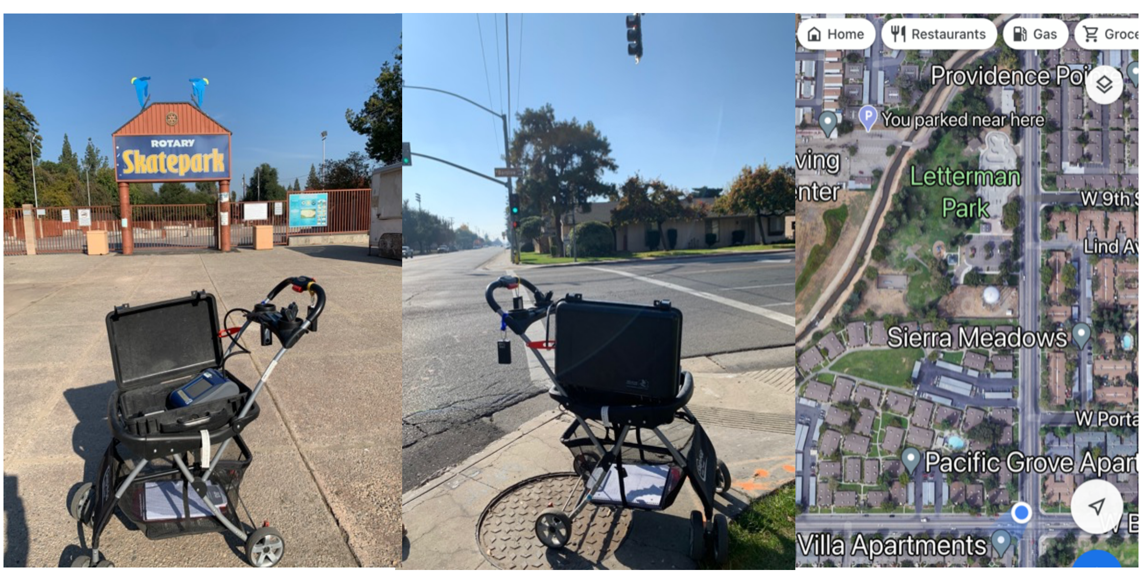
ID	zip	Repeat	Date	Latitude	Longitude	PM2.5	BC	PAHs	BC/ PM2.5	PAHs/ PM2.5	PAHs/ BC
B6-93703-R44	93703	3rd	6/7/2017	36.772	-119.736	19.3	1.3	0.103	7%	0.53%	7.95%
B6-93703-R44	93703	4th	6/7/2017	36.772	-119.736	22.4	0.9	0.083	4%	0.37%	8.91%
B6-93703-R44	93703	5th	6/7/2017	36.772	-119.736	14.4	0.6	0.108	4%	0.75%	18.59%
B6-93703-R44	93703	6th	6/7/2017	36.772	-119.736	27.3	0.9	0.144	3%	0.53%	16.50%
B6-93704-R45	93704	1st	5/31/2017	36.768	-119.809	5.2	0.3	0.073	6%	1.40%	23.82%
B6-93704-R45	93704	2nd	6/13/2017	36.768	-119.809	28.8	0.4	0.097	1%	0.34%	27.41%
B6-93704-R45	93704	3rd	6/13/2017	36.768	-119.809	27.7	0.3	0.114	1%	0.41%	41.07%
B6-93704-R45	93704	4th	6/13/2017	36.768	-119.809	27.6	0.5	0.143	2%	0.52%	30.91%
B6-93722-R46	93722	1st	6/1/2017	36.764	-119.889	16.5	0.8	0.049	5%	0.30%	5.99%
B6-93722-R47	93722	1st	6/1/2017	36.779	-119.857	15.9	0.4	0.080	3%	0.50%	19.78%
B6-93722-R48	93722	1st	6/1/2017	36.801	-119.853	13.1	NA	0.062	NA	0.47%	NA
B6-93722-R48	93722	2nd	6/8/2017	36.801	-119.853	27.6	0.7	0.067	2%	0.24%	9.75%
B6-93722-R48	93722	3rd	6/8/2017	36.801	-119.853	25.2	0.4	0.068	2%	0.27%	15.25%
B6-93722-R48	93722	4th	6/8/2017	36.801	-119.853	23.2	0.4	0.071	2%	0.31%	19.65%
B6-93722-R48	93722	5th	6/15/2017	36.801	-119.853	28.7	0.8	0.130	3%	0.45%	15.63%
B6-93722-R48	93722	6th	6/15/2017	36.801	-119.853	28.0	0.7	0.126	2%	0.45%	18.81%
B6-93722-R48	93722	7th	6/15/2017	36.801	-119.853	27.8	0.7	0.131	2%	0.47%	18.95%
B6-93722-R48	93722	8th	6/15/2017	36.801	-119.853	27.8	0.7	0.116	2%	0.42%	17.58%
B6-93722-R49	93722	1st	6/1/2017	36.826	-119.883	5.2	0.4	0.117	7%	2.23%	31.74%
B6-93711-R50	93711	1st	6/1/2017	36.837	-119.846	3.9	0.2	0.069	5%	1.76%	38.41%
B6-93650-R51	93650	1st	6/1/2017	36.846	-119.79	3.8	0.2	0.149	5%	3.87%	77.56%
B6-93705-R52	93705	1st	6/5/2017	36.798	-119.8353	13.9	0.3	0.094	2%	0.68%	29.71%
B6-93705-R53	93705	1st	6/2/2017	36.786	-119.79	5.2	0.5	0.054	10%	1.03%	10.27%
B6-93726-R54	93726	1st	6/2/2017	36.806	-119.772	13.7	0.4	0.119	3%	0.87%	28.90%
B6-93710-R55	93710	1st	6/2/2017	36.815	-119.766	13.6	0.4	0.106	3%	0.78%	25.14%
B6-93612-R56	93612	1st	6/2/2017	36.859	-119.697	12.8	0.5	0.090	4%	0.70%	17.26%

Table A-2 Correlation Coefficients and p-values

	Black Carbon	PM2.5	BC/PM2.5	Traffic	Diesel.PM Emission	Walk.score	CES.Pollution.Burden.Score	CES.Population.Characteristics.Score	CES.Total.Score	Disorder	Order	Asthma	Low.Birth.Weight
Black Carbon	1												
P-value	NA												
PM2.5	**0.49**	1											
P-value	**0.041**	NA											
BC/PM2.5	0.41	**-0.53**	1										
P-value	0.09	**0.024**	NA										
Traffic	-0.26	-0.34	0.18	1									
P-value	0.30	0.16	0.47	NA									
Diesel.PM.Emission	-0.17	-0.22	0.14	**0.87**	1								
P-value	0.51	0.38	0.59	**0.000003**	NA								
Walk.score	-0.13	**-0.51**	**0.56**	**0.73**	**0.87**	1							
P-value	0.64	**0.044**	**0.025**	**0.00124**	**0.00001**	NA							
CES.Pollution.Burden.Score	-0.17	-0.14	-0.07	0.06	-0.10	-0.30	1						
P-value	0.50	0.58	0.78	0.82	0.68	0.25	NA						
CES.Population.Characteristics.Score	-0.03	-0.10	0.06	0.46	0.59	0.39	0.35	1					
P-value	0.92	0.69	0.83	0.055	0.010	0.13	0.15	NA					
CES.Total.Score	-0.07	-0.12	0.00	0.31	0.34	0.11	**0.75**	**0.88**	1				
P-value	0.79	0.64	0.99	0.22	0.17	0.69	**0.00036**	**0.000001**	NA				
Disorder	0.07	0.20	-0.04	0.45	**0.59**	0.34	-0.32	0.40	0.11	1			
P-value	0.78	0.43	0.88	0.063	**0.010**	0.20	0.19	0.10	0.65	NA			
Order	-0.37	-0.43	0.21	0.45	0.32	**0.53**	-0.27	-0.13	-0.26	0.26	1		
P-value	0.13	0.08	0.41	0.060	0.19	**0.036**	0.27	0.60	0.29	0.30	NA		
Asthma	0.02	-0.11	0.14	0.44	**0.67**	**0.56**	0.24	**0.92**	**0.78**	0.43	-0.10	1	
P-value	0.93	0.66	0.59	0.07	**0.0024**	**0.024**	0.34	**0.00000**	**0.00014**	0.08	0.70	NA	
Low.Birth.Weight	-0.09	-0.16	0.12	**0.62**	**0.65**	**0.49**	0.31	**0.77**	**0.69**	0.24	0.23	**0.79**	1
P-value	0.72	0.52	0.65	**0.0061**	**0.0033**	**0.053**	0.21	**0.00017**	**0.00148**	0.35	0.36	**0.0001**	NA

Figure A-1. Collocation Measurement near Clovis monitoring station

Figure A-2. Mobile Test Near Clovis Monitoring Station



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