



LAWRENCE  
LIVERMORE  
NATIONAL  
LABORATORY

# PurpleAir Sensors as Effective Indicators of PM Exposure in Urban Areas

M. D. DeLong-Maxey

August 4, 2022

## **Disclaimer**

---

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

# PurpleAir Sensors as Effective Indicators of PM Exposure in Urban Areas

LLNL-TR-838504

Delong-Maxey, Morgan Dakota  
8-4-2022



## PurpleAir Sensors as Effective Indicators of PM Exposure in Urban Areas

Author: Morgan Dakota DeLong-Maxey

### Abstract

Particulate matter that is 2.5 microns or less in diameter (PM<sub>2.5</sub>) is a byproduct of combustion reactions used for energy production. Populations that are exposed to consistently high levels of aerosolized PM<sub>2.5</sub> face serious health risks. This project compared low-cost PM<sub>2.5</sub> sensors with federally recognized methods to look for a cost-effective way to expand the air quality monitor network. Within metropolitan areas that face inconsistent spatial distribution of PM<sub>2.5</sub>, there may not be the necessary network density to indicate neighborhood-levels of PM<sub>2.5</sub>. This project aimed to examine the sensitivity of low-cost PM<sub>2.5</sub> sensor measurements on a neighborhood scale (< 4 km diameter) in an urban area to prevent citizens from being exposed to unsafe levels of PM<sub>2.5</sub> without their knowledge. Using publicly available sensor data from Livermore, CA and Bakersfield, CA, it was determined, based on the revealed patterns, that the analyzed low-cost sensors were able to display representative PM<sub>2.5</sub> levels for neighborhood-scale areas exposed to pollution from PM<sub>2.5</sub> sources.

### Introduction

The American Lung Association (ALA) has put out a “State of the Air” report every year since 2000. The most recent report has found that while we have seen steady successes due to the Clean Air Act, there are rising challenges due to climate change impacts, and over 20 million people still live in counties in the United States where year-round particle pollution (PM) levels exceed national air quality limits. There are also environmental justice issues associated with PM exposure. The burden of bad air quality is unequally shared; people of color are 3.6 times as likely as white people to live in a county with a failing grade for both particulate matter and ozone.<sup>1</sup>

A major component of the ALA annual report is the concentration of atmospheric PM. PM in the air comes from either direct emissions or chemical reactions in the atmosphere. PM can contain components of nitrates, sulfates, elemental carbon, organic carbon compounds, acid aerosols, trace metals, and geological materials. However, PM is differentiated based on its size, rather than the components. PM is divided into PM that is 10 microns or less and 2.5 microns or less in diameter, indicated as PM<sub>10</sub> and PM<sub>2.5</sub> respectively.<sup>2</sup>

PM<sub>2.5</sub> has been designated as one of the leading contributors to the global burden of disease because their small size allows them to penetrate deep into the lungs, greatly impacting human health.<sup>3,4</sup> For instance, long-term exposure to PM<sub>2.5</sub> is associated with premature death and reduced lung function growth in children.<sup>5</sup> In the US, up to 5% of annual deaths are attributed to exposure to PM<sub>2.5</sub>.<sup>6</sup>

There are primary and secondary sources of PM<sub>2.5</sub>. Examples of primary sources include wildfires, industrial facilities, and vehicles. Secondary sources are those that emit the pre-cursors to PM<sub>2.5</sub> that chemically react in the atmosphere producing PM<sub>2.5</sub>. These sources include factories, vehicles, construction sites, power plants, and coal fires. For instance, emissions from

power plants includes sulfur dioxide, nitrogen oxides, CO<sub>2</sub>, and other pollutants, and sulfur dioxide and nitrogen oxides that can form into PM<sub>2.5</sub> in addition to ozone.<sup>7</sup> From sources like power plants, fine particles can form from reactions between gases and water droplets in the atmosphere miles from the original source of the emissions.<sup>8</sup> In addition to these sources, Stanford researchers observed, in a 14-year analysis of California air quality, higher levels of air pollutants in the proximity (~2.5 miles) of oil and gas wells. These air pollutants include both PM<sub>2.5</sub> and its precursors.<sup>9</sup>

The US depends on the Environmental Protection Agency (EPA) air quality monitoring stations (AQMS) to determine the PM<sub>2.5</sub> concentration in given areas. However, they are required to use either federal reference methods (FRM) or federal equivalent methods (FEM) to measure. These methods use gravimetric measurement of a filter and beta ray attenuation, respectively.<sup>10</sup> These are reliable methods for determining the concentration of PM<sub>2.5</sub>. However, each costs thousands of dollars, has limited ranges and fixed locations, and requires calibration, maintenance, and trained personal. This means that, when only relying on the sparsely dispersed FRM and FEM monitors, we may not be seeing the inconsistent spatial distribution of PM<sub>2.5</sub> within vulnerable communities. Therefore, an expanded and denser network is needed to see the true impact of PM<sub>2.5</sub> emissions.<sup>6</sup>

To address this need, the objective of this project was to examine the measurements made by low-cost air quality sensors against those of FEM and FRM monitors and determine if they could provide an expanded and more detailed view of PM<sub>2.5</sub> exposure in urban areas. This project used PurpleAir sensors (PA) (priced at < \$300) because of the network's publicly available data and their ever-increasing global network.<sup>11</sup>

PA sensors have been found to have biases related to relative humidity and high ambient PM levels along with errors associated with particle size distribution and chemical composition of the ambient air. Therefore, past studies have often used PA sensors collocated to FRM or FEM equivalent monitors to determine a correction factor for area-wide PA sensors, according to the discrepancies seen in the collocated PA sensor. However, since PA sensors are installed by citizens, their dispersion through communities does not guarantee that there will be a PA monitor collocated with either a FEM monitor or a FRM monitor.<sup>6</sup> Therefore, this project aimed to examine how the sensitivity of non-collocated PA sensor measurements compare to those of FEM or FRM monitors in order to determine if PA sensors effectively indicate neighborhood scale (< 4 km diameter) levels of PM<sub>2.5</sub>.

To do this, data was gathered from two locations in the state of California. Data from PA sensors across the town of Livermore, CA and a FEM monitor located at Lawrence Livermore National Laboratory (LLNL) was gathered to examine underlying patterns that may be seen between an FEM monitor and PA sensors to serve as a comparison for the larger metropolitan area that the objective of this project targets. Since the aim was to examine PAs within an urban area that suffers from variable PM<sub>2.5</sub> exposure due to energy production facilities, Bakersfield, CA was selected as an appropriate candidate. Bakersfield, the seat of Kern County, has a population of more than 400,000 and was ranked as the city with the worst annual PM levels in America by the ALA.<sup>12</sup> Kern County is also known for its ties to the oil and gas industry and,

consequently, hosts associated PM<sub>2.5</sub> emissions sources.<sup>13</sup> Regarding health indicators, 9% of children and 8% of adults in Bakersfield have asthma, which are slightly higher than the national averages.<sup>14</sup>

## Methods

### *Instruments*

Met One Beta Attenuated Monitor (BAM-1022) at LLNL, an FEM monitor, is calibrated according to the federal methods for measuring ambient concentrations of PM<sub>2.5</sub>. This "equivalent method" is in accordance with Title 40, Part 53 of the Code of Federal Regulations (40 CFR Part 53).<sup>15</sup> A BAM monitor uses the radioactive decay of Carbon 14 to determine the presence of particulate matter. First, a vacuum is used to pump in the ambient air surrounding the monitor, then the particles stick to a tape that is automatically changed every hour to enable hourly PM measurements. To measure the PM<sub>2.5</sub> that is taken in from the environment and rests on the tape, the beta rays emitted from the radioactive decay of a C-14 source are measured from the other side of the tape. The more particles there are, the more they will block the beta decay. Therefore, if less beta decay is recorded through the tape, then there is more particulate matter blocking the beta particles. A BAM monitor can determine both volume and mass. Unlike Purple Air, it does not have to estimate the mass to determine density.<sup>16</sup>

PA sensors are pre-calibrated by the manufacturer. PA units have two laser-based sensors and an environmental sensor that monitors pressure, temperature, and humidity.<sup>17</sup> Fans draw particles into the sensors, past the lasers contained in each of the units. The number of particles is calculated by determining the number of pulses from the laser and converting this to a mass concentration using an outdoor PM algorithm. The mass concentration measurement determined by PA units is calculated based on the measured volume of the particulates and an estimated average density that is built into the algorithm. Therefore, if the density of the particles varies, it is likely that the PA measurements will not have as high of an accuracy as FEM or FRM based monitors that are able to determine the mass and volume of the particles measured.<sup>6</sup>

Bakersfield data was gathered from a FEM monitor and a FRM monitor. The FEM and FRM monitors in Bakersfield, CA are listed on the California Air Resources Board (CARB) website, respectively, as "Bakersfield-California Avenue" (BCA) and "Bakersfield-Golden" sensor (BGS). BCA is a FRM monitor, specifically a R & P Model 2025 PM-2.5 Sequential Air Sampler w/VSCC (a gravimetric method). BGS is a FEM monitor, specifically a Met One BAM-1020 Mass Monitor w/VSCC (using the beta attenuation method).<sup>18, 19, 20</sup> FRM systems are filter-based monitors where samples are collected based on the local organization determined schedule. A benefit of FRM monitors is the ability to analyze the PM speciation from the filter samples, aiding PM research efforts.<sup>19</sup>

### *Data collection and analysis:*

#### Livermore.

To create a basis of understanding of PA sensor patterns, data was gathered from 30 PA sensors in Livermore, CA, and the one BAM monitor at LLNL. Hourly concentrations ( $\mu\text{g}/\text{m}^3$ )

of PM<sub>2.5</sub> were collected from March 2022 from all sources. This data was then processed to produce the average daily PM<sub>2.5</sub> concentrations.

After gathering and processing the data, the PA monitors were ordered by distance from the BAM monitor. Based on this staggered order, the PA monitor outputs were compared to the BAM monitors. PA monitors were grouped into neighborhoods to examine the patterns between neighborhood PA measurements and the BAM monitor.

### Bakersfield.

Using the PA patterns observed in Livermore, the effectiveness of PA sensors as indicators of PM<sub>2.5</sub> was analyzed in Bakersfield, CA. Hourly PM<sub>2.5</sub> data from both FRM and FEM monitors in Bakersfield were gathered from the California Air Resource Board (CARB) website for the month of March 2022. Likewise, from the PurpleAir website, hourly data from 18 PA sensors was gathered. This data was then processed to produce the average daily PM<sub>2.5</sub> concentrations.

In addition to the air-quality monitor data, information on the locations of known sources of PM<sub>2.5</sub> was also gathered from the CARB website. Additional information on the locations of oil and gas wells was also obtained.<sup>21</sup> This information was mapped, and sources were associated with each of the examined monitors (Table 2 & Figure 7) to see how fossil-fuel-related and non-fossil-fuel-related sources may influence any variations in the PM<sub>2.5</sub> measurements recorded by PA and FEM air quality monitors.

### *Statistical analysis:*

In Livermore, each PA sensor's monthly data was compared to the BAM's corresponding measurements using RStudio to determine the associated P values, R<sup>2</sup> values, and Spearman correlation values, as listed in Table 1. To evaluate the overall trends of the PA units compared to the FEM monitor, regression tests were conducted. The FEM was compared to all the PA units in its area based on daily PM<sub>2.5</sub> measurements. The Spearman correlation test was conducted to determine the strength and direction of the monotonic association between the variables.<sup>22</sup> In Bakersfield, the same values were determined, with each of the FEM and FRM monitor being paired to individual PA sensors (Table 3 and 4). ANOVA tests were also run on groups of sensors that fell within 4 km of each other to determine the variance between neighborhood data sets.

## **Results and Discussion**

### *Results.*

#### Livermore.

The processing of PA sensor measurements revealed that PA sensors numbered 4, 8, 14, 17, 19, and 22 contained significant portions of time within the month of March 2022 when PM<sub>2.5</sub> measurements were recorded as 0. It would be highly irregular to have extended periods of time in which measurements were at 0. These measurements are also uncharacteristic in comparison to the surrounding PA monitor measurements. Therefore, while these sensors were

included in the overview of the PA sensors observed to understand the percentage of monitors that may display these conflicting measurements, they are not used in neighborhood comparisons or averaged statistical values.

The examination of air monitor data from PA sensors and a FEM (BAM-1022) in Livermore, CA revealed that the relationship between PA sensor data and FEM monitor data did not have a strong linear relationship, as indicated by the  $R^2$  values in Table 1. Based on the graphed BAM vs. averaged PA values in Figure 1, it was impossible to determine if there exists a monotonic relationship. Therefore, the Spearman correlation test was run to determine the strength and direction of a monotonic relationship. As indicated in Table 1, The  $R^2$  values associated with linear regression models of BAM and individual PA sensors averaged  $0.36 \pm 0.02$ , indicating a non-linear relationship. However, running spearman correlation tests on the same paired variables, averaged  $0.44 \pm 0.02$ . This means that there was a positive correlation between the data sets that displayed moderate strength, but there was a certain amount of variability along a monatomic relationship.

Livermore BAM-1022 and PA Statistical Analysis Results

Label	PurpleAir Name	P value	$R^2$	r (Spearman correlation)	Distance from BAM (in miles)
PA_1	914 grey fox circle	0.80490	0.40	0.48	7.16
PA_2	Altamont Cir (outside)	0.10630	0.38	0.49	1.83
PA_3	amoeba (outside)	0.69290	0.37	0.46	3.77
PA_4*	Arlene and Patterson Pass (outside)	0.01711	0.25	0.21	0.31
PA_5	ARROYO CROSSINGS (outside)	0.94100	0.37	0.43	3.20
PA_6	Aspen Ct (outside)	0.03857	0.32	0.43	1.74
PA_7*	Bartlett Place (outside)	0.63980	0.34	0.43	8.91
PA_8	Cars may not stop (outside)	0.20190	0.38	0.46	8.98
PA_9	Central Parkway (outside)	0.15200	0.40	0.48	7.01
PA_10	Chardonnay (outside)	0.26770	0.33	0.38	7.56
PA_11	Chateau (outside)	0.85190	0.38	0.44	2.76
PA_12	Chateau-PL (outside)	0.84870	0.37	0.42	3.13
PA_13	Del Valle Pkwy (outside)	0.53260	0.31	0.39	9.09
PA_14*	Division (outside)	0.00002	0.23	0.22	9.37
PA_15	Dublin Onyx (outside)	0.30890	0.40	0.49	6.97
PA_16	Dublin Ranch (outside)	0.27850	0.39	0.50	8.38
PA_17*	East Sunset (outside)	0.00001	0.21	0.22	3.66
PA_18	Fairlands Park (outside)	0.02812	0.39	0.45	8.73
PA_19*	T's Garden (outside)	0.00022	0.22	0.20	1.74
PA_20	Oak Home (outside)	0.67350	0.38	0.44	1.84
PA_21	Outside (outside)	0.21290	0.36	0.42	1.74
PA_22*	PAII-Drake4042 (outside)	0.00000	0.24	0.21	2.06
PA_23	Mine (outside)	0.04446	0.34	0.42	2.89

PA_24	Valley Montessori School (outside)	0.02325	0.38	0.44	3.05
PA_25	Lucca Circle (outside)	0.14920	0.38	0.47	2.91
PA_26	Livermore Mars (outside)	0.88440	0.33	0.39	4.43
PA_27	South Livermore - Hansen (outside)	0.46730	0.30	0.33	4.14
PA_28	Winery (outside)	0.33790	0.46	0.59	2.24
PA_29	Los Alamos (outside)	0.36620	0.26	0.30	4.28
PA_30	Stonebridge Rd (outside)	0.38070	0.35	0.39	4.49

Table 1: displays the results of the statistical analysis conducted on the data collected from the air quality monitors in Livermore, CA. \* indicates abnormalities observed in collected data.

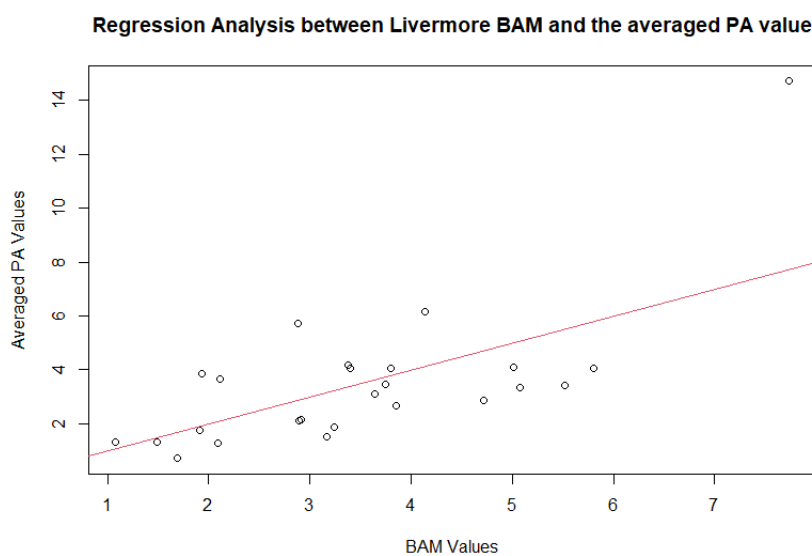


Figure 1: This scatter plot indicates the relationship between BAM-1022 measured daily values and averaged PA monitor measured daily values. The red line equals  $y=x$ .

While analysis suggests that the data tends toward a more monotonic than linear relationship, the graphing of neighborhood-grouped PAs and BAM daily concentrations ( $\mu\text{g}/\text{m}^3$ ) of  $\text{PM}_{2.5}$  illustrate that PA sensors are able to track the variability of concentrations across time to a degree that would successfully indicate neighborhood exposure to hazardous levels of  $\text{PM}_{2.5}$ .

Based on neighborhood groupings, as seen in Figures 2 to 4, PA sensor measurements can track above and below BAM measurements. This suggests that even if there is a uniform discrepancy in FEM versus PA measurements that it will not curb PA sensors from indicating if there are high levels of  $\text{PM}_{2.5}$ . If anything, as indicated by peaks on March 4<sup>th</sup> and 25<sup>th</sup> in Figures 2 to 4, PA monitors may overestimate  $\text{PM}_{2.5}$  levels at higher concentrations. This demonstrates how PA sensors can indicate if there are unique  $\text{PM}_{2.5}$  levels on a neighborhood-scale that may go undetected by a singular FEM monitor.

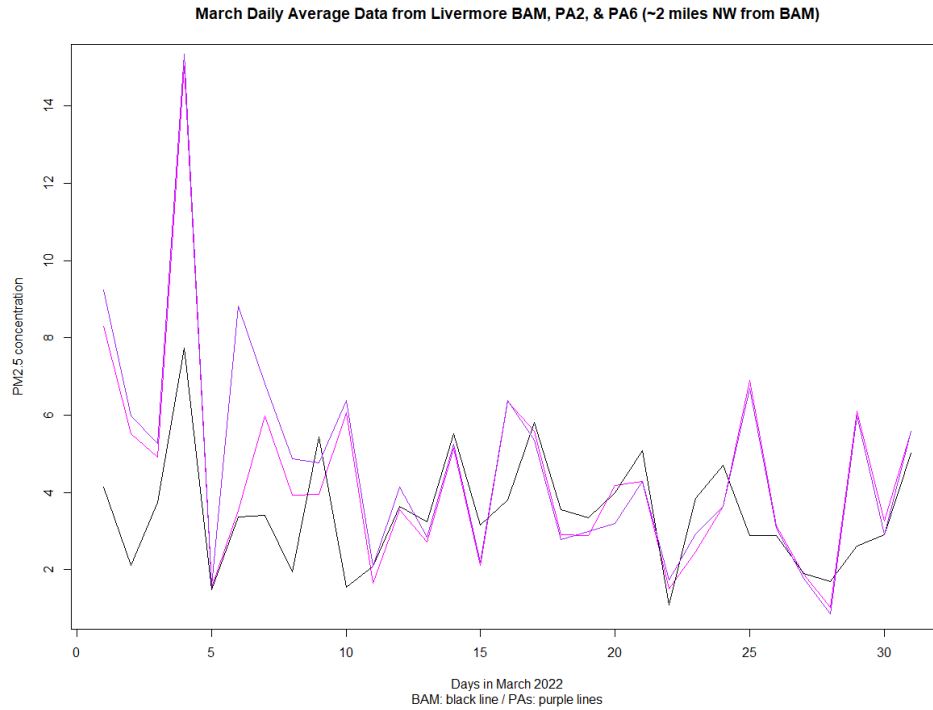


Figure 2: This figure presents daily  $PM_{2.5}$   $\mu g/m^3$  measurements over time (March 2022) for the Livermore (FEM) and two PA Sensors (2 & 6) that are located ~2 miles NW from the FEM monitor. The purple, and magenta lines representing the PA monitors measurements are more in agreement than the black line, representing the FEM monitor. However, all the lines register parallel peaks and dips in  $PM_{2.5}$  measurements.

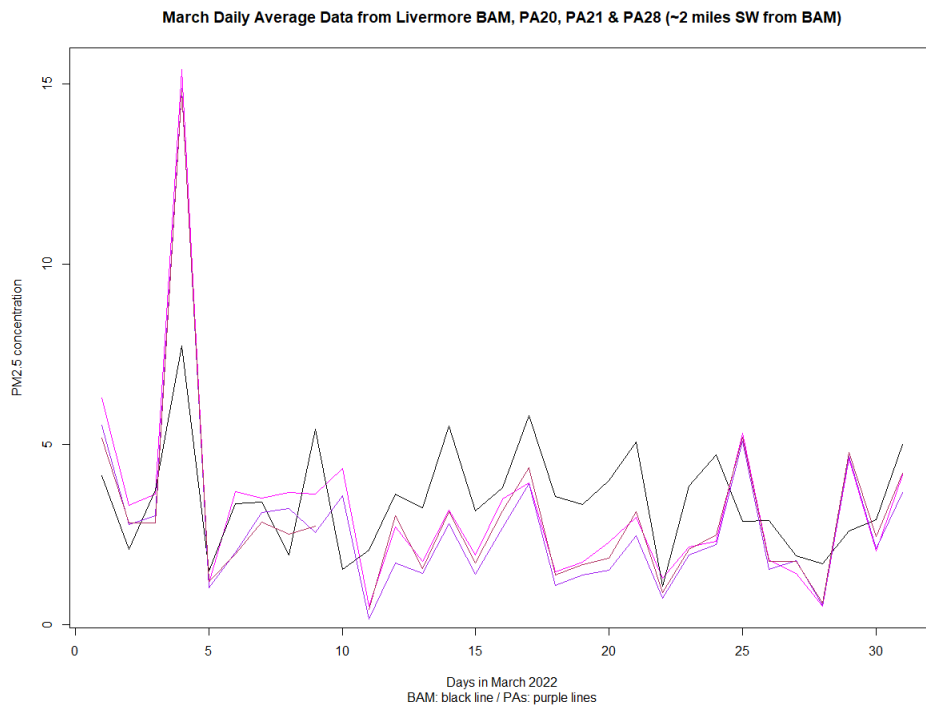
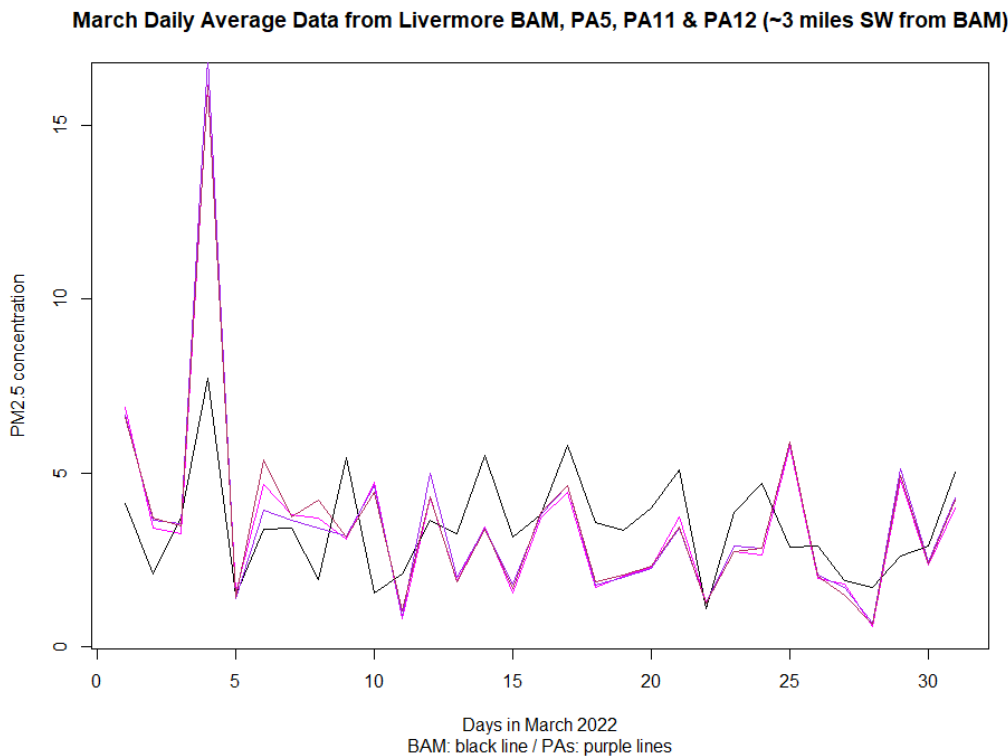


Figure 3: This figure presents daily  $PM_{2.5}$   $\mu g/m^3$  measurements over time (March 2022) for the Livermore (FEM) and three PA Sensors (20, 21, and 28) located ~2 miles SW from the FEM monitor. The purple, maroon, and magenta lines representing the

*PA monitors measurements are more in agreement than the black line, representing the FEM monitor. However, all the lines register parallel peaks and dips in PM<sub>2.5</sub> measurements.*



*Figure 4: This figure presents daily PM<sub>2.5</sub> µg/m<sup>3</sup> measurements over time (March 2022) for the Livermore (FEM) and three PA Sensors (5, 11, & 12) located ~3 miles SW from the FEM monitor. The purple, maroon, and magenta lines representing the PA monitors measurements are more in agreement than the black line, representing the FEM monitor. However, all the lines register parallel peaks and dips in PM<sub>2.5</sub> measurements.*

### Bakersfield.

As seen in the comparison of Bakersfield's FRM and FEM monitors (Figure 6), BGS consistently trends higher than BCA, but picks up the same peaks as BCA. This variation is most logically explained by the proximity of a highway to BGS, as seen in Figure 5. This variation in PM<sub>2.5</sub> measurements 5.4 km apart demonstrates the need to understand how PM<sub>2.5</sub> may vary across the city.

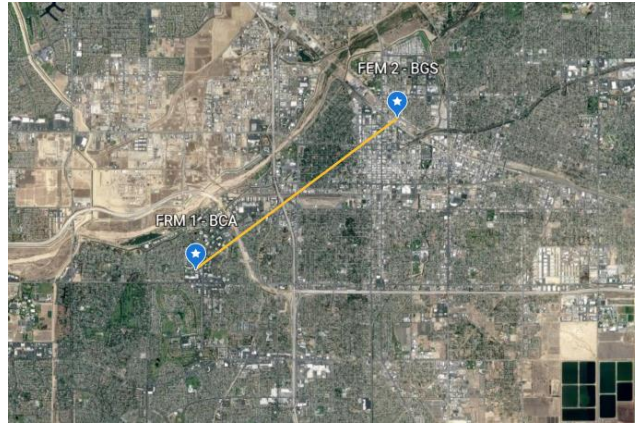


Figure 5: This map displays the plotted locations of the FEM and FRM monitors in Bakersfield, CA. The marker to the top-right of the figure represents the “Bakersfield-Golden.” (BGS) monitor that is a FEM monitor, specifically a Met One BAM-1020 Mass Monitor. The marker on the bottom-left represents the “Bakersfield-California Avenue” (BCA) monitor, a FRM monitor, specifically a R & P Model 2025 PM-2.5 Sequential Air Sampler. This figure was captured from Google Maps after mapping data from CARB.<sup>18,23</sup>

#### Daily average data from Bakersfield BGS & BCA monitors

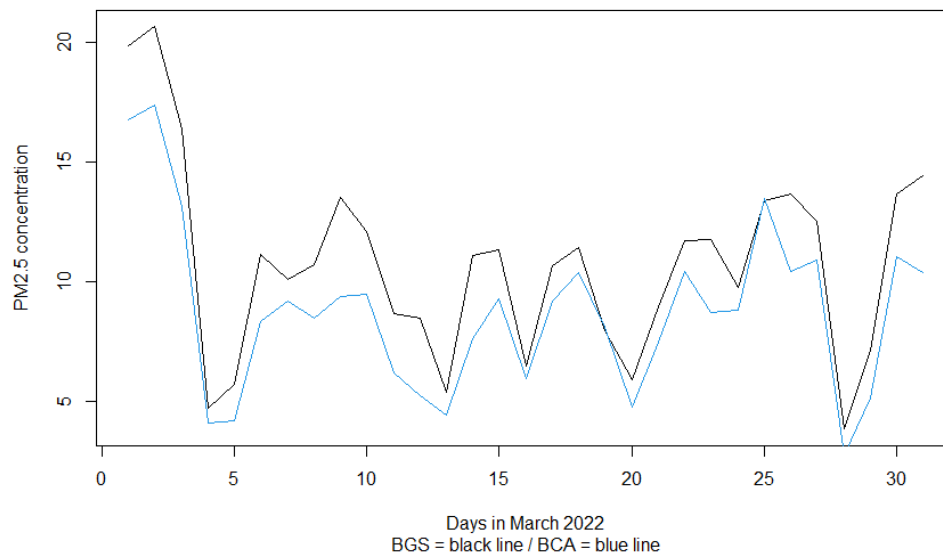


Figure 6: This figure presents daily PM<sub>2.5</sub> µg/m<sup>3</sup> measurements over time (March 2022) for the Bakersfield BGS (FEM) and BCA (FRM) monitors, represented by the black and blue lines respectively.

The characterization of PM<sub>2.5</sub> emissions sources that impact Bakersfield, CA revealed sources that include oil wells, natural gas power plants, agriculture practices, a municipal airport, highways, small oil refineries, and industrial sources, as seen in Figure 7 and 8. The mapped spatial distribution of these sources revealed the proximity of PA, FRM, and FEM monitors to these sources, as listed in Table 2.

## Location and Characteristics Associated with PA Sensors in Bakersfield, CA

PA	Latitude	Longitude	Neighborhood proximity (other monitors within 4km)	Proximal Sources of Emission
1	35.35489	-119.02624	3, BCA, BGS	RE, PP
2	35.38944	-119.11168	7, 9, 14	RE
3	35.34952	-119.03717	1, BCA	HW, RE
4	35.38852	-118.94917	16	RE
5	35.35019	-119.09403	6, 7, 14, 15, BCA	RE, PP
6	35.33081	-119.10963	5, 7, 11, 14, 15	PP, RE, OW
7	35.3595	-119.11425	5, 6, 9, 14	HW, RE, OW
8	35.39989	-118.9968	BGS	RF, PP
9	35.36545	-119.13663	2, 7, 14	RE, HW, OW
10	35.32522	-118.99885		AP
11	35.32961	-119.14298	6, 14, 15	RE, PP, AG, FA, OW
12	35.44573	-119.11592		RE, PP, AG, RF
13	35.40246	-118.86711	17, 18	OW
14	35.36062	-119.12815	2, 5, 6, 7, 9, 11	RE, OW
15	35.32215	-119.11547	5, 6, 11	RE, AG, PP, RF, OW
16	35.40146	-118.91417	4	RE, PP
17	35.41881	-118.85145	13, 18	OW
18	35.40107	-118.83779	13, 17	OW

PP=Power Plant, RF=Refinery, OW=Oil well, HW=Highway, RE=Residential, AG=Agriculture, AP=Airport, FA=other type of PM<sub>2.5</sub> producing facility

*Table 2: This table presents the Bakersfield PA monitors' allocated number, location, neighboring air quality monitors, and closest sources of PM<sub>2.5</sub> emissions.*

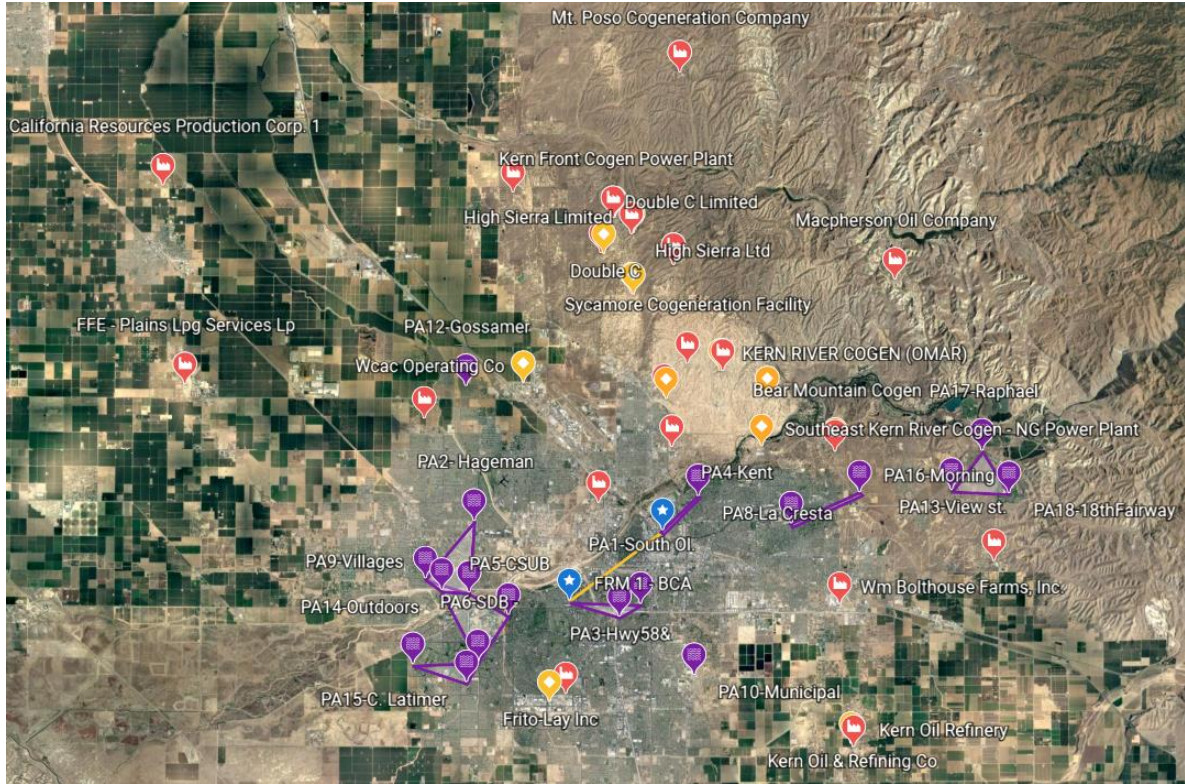


Figure 7: This figure displays the mapped PA sensors (purple markers), created PA neighborhoods (purple boxes), natural gas power plants (yellow markers), and CARB-reported sources of PM<sub>2.5</sub> emission (red markers) which represent both those that are and those that are not oil and gas-related facilities. This figure was captured from Google Maps after mapping data from PurpleAir, CARB, and the California Energy Commission.<sup>23, 24, 25, 26</sup>

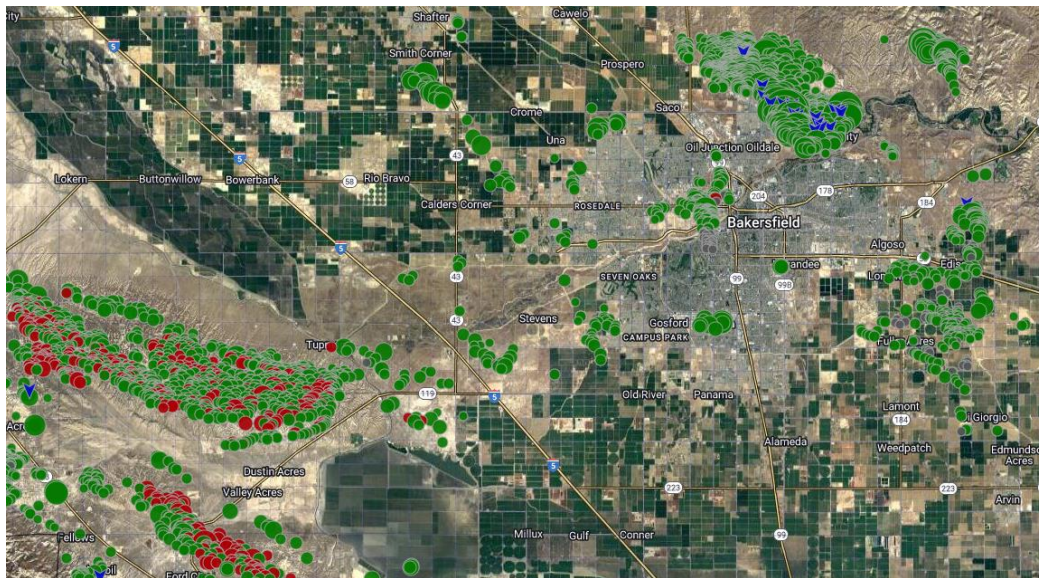


Figure 8: This map shows the natural gas and oil wells located in Kern County. The active oil wells are indicated by the green circles and the active natural gas wells are indicated by the red circles. This map was captured from ShaleXP's Oil & Gas Research and Visualization Tool.<sup>21</sup>

The statistical examination of air monitor data in Bakersfield also indicated that the relationship among PA sensor data, and FEM and FRM monitor displays monotonic characteristics. When comparing BGS and the 18 PAs in Bakersfield, the average  $R^2$  value was  $0.49 \pm 0.02$  and the average  $r$  was  $0.67 \pm 0.03$ . The comparison between the PAs and the BCA monitor resulted in an averaged  $R^2$  value of  $0.36 \pm 0.02$  and an averaged  $r$  value of  $0.52 \pm 0.02$ . These results along with the data graphed against time, as seen in Figures 10 to 17, suggest that the monotonic nature of these matched variables is due to PA sensors tendency to overestimate  $PM_{2.5}$  concentrations at higher ambient levels of pollution, while underestimating when there is less pollution. This would result in a moderately linear, but strong and positive monotonic relationship.

### BGS and PA Analysis

PA	Name	distance from BGS (miles)	P value	$R^2$	$r$ (Spearman Correlation)
8	La Cresta (outside)	1.43	0.18	0.48	0.62
1	South Oleander (outside)	2.2	0.01	0.58	0.74
3	Hwy58 & Hwy99 (outside)	2.78	0.20	0.58	0.74
4	Kent (outside)	3.7	0.02	0.39	0.63
10	Municipal Airport - Hosted by TDH (outside)	4.22	>0.00	0.56	0.72
5	CSUB (outside)	5.1	0.93	0.49	0.63
2	Hageman & Calloway (outside)	5.5	0.75	0.48	0.61
16	MorningStar (outside)	5.8	>0.00	0.55	0.78
7	Brookdale Riverwalk (outside)	5.9	0.98	0.48	0.65
6	SDB (outside)	6.53	0.19	0.48	0.62
14	Outdoors Southwest Bakersfield, CA (outside)	6.6	0.10	0.51	0.69
9	Villages of Brimhall (outside)	7.01	0.90	0.48	0.63
12	Gossamer Grove (outside)	7.05	0.20	0.50	0.64
15	C. Latimer backyard (outside)	7.16	0.51	0.48	0.60
11	Oakley St. (outside)	8.2	0.19	0.44	0.59
13	View St (outside)	8.4	0.30	0.49	0.74
17	Raphael Ave. (outside)	9.51	0.11	0.44	0.70
18	18th Fairway (outside)	9.54	0.01	0.45	0.71

Table 3: This table, arranged based on PA sensor distance from the BGS monitor, presents individual Bakersfield PA sensor's comparison to the BGS monitor, listing their distance and statistical comparisons.

### BCA and PA Analysis

PA	Name	distance from BCA (miles)	P value	$R^2$	$r$ (Spearman Correlation)
3	Hwy58 & Hwy99 (outside)	1.53	0.01	0.43	0.58
5	CSUB (outside)	1.81	0.10	0.37	0.49
1	South Oleander (outside)	2.07	0.41	0.45	0.58
7	Brookdale Riverwalk (outside)	2.9	0.13	0.37	0.51

6	SDB (outside)	3.2	0.01	0.38	0.48
2	Hageman & Calloway (outside)	3.58	0.33	0.36	0.45
14	Outdoors Southwest Bakersfield,CA (outside)	3.7	> 0.00	0.39	0.54
15	C. Latimer backyard (outside)	3.8	0.04	0.37	0.47
9	Villages of Brimhall (outside)	4.2	0.11	0.38	0.51
10	Municipal Airport - Hosted by TDH (outside)	4.2	> 0.00	0.42	0.54
8	La Cresta (outside)	4.8	0.01	0.38	0.48
11	Oakley St. (outside)	4.9	0.98	0.34	0.47
4	Kent (outside)	6.8	> 0.00	0.24	0.45
12	Gossamer Grove (outside)	6.8	0.01	0.37	0.48
16	MorningStar (outside)	8.9	> 0.00	0.37	0.60
13	View St (outside)	11.5	0.70	0.32	0.59
17	Raphael Ave. (outside)	12.8	0.88	0.28	0.58
18	18th Fairway (outside)	13.8	0.19	0.29	0.59

*Table 4: This table, arranged based on PA sensor distance from the BCA monitor, presents individual Bakersfield PA sensor's comparison to the BCA monitor, listing their distance and statistical comparisons*

The grouping of 2 to 4 PA sensors into neighborhoods whose diameter did not exceed 4 km (Figure 9) allowed for comparisons of PM<sub>2.5</sub> concentrations on a neighborhood scale versus the FEM and FRM measured concentrations. To test the similarity of the measured data on the neighborhood scale, ANOVA tests were conducted to compare the PA sensor measurements. These tests revealed the data presented in Table 5. With alpha set at 0.05, P values > 0.05 indicate that the PM<sub>2.5</sub> measurements within the associated neighborhood fall within a 95% confidence interval. The graphing of this data along with the statistical analysis revealed that, besides neighborhoods B and D, the PA monitors within these neighborhood parameters measured very similar PM<sub>2.5</sub> level trends. As seen in Figures 10 to 17, the monitors within the observed neighborhoods also tend to track much closer to each other than to the FEM and FRM monitors graphed with them. The contrasts seen in the neighborhood levels versus the FEM and FRM levels illustrates PA sensors' potential ability to signal harmful levels of PM<sub>2.5</sub> that are only seen on the neighborhood-scale.

Beyond the similarity of the PA measurements within neighborhoods, Figures 10 to 17 demonstrate how neighborhood PAs also share the same relationship with the FEM and FRM monitors. All monitors register parallel peaks and dips in PM<sub>2.5</sub> measurements.

**Bakersfield PA Neighborhood Groups and P values**

Neighborhoods	Monitors	P value
A	13, 17, 18	0.356
B	4, 16	3.1e-07
C	8, BGS	0.183
D	1, 3, BCA	0.00136
E	2, 7, 9	0.926

F	7, 9, 14	0.261
G	5, 6, 7, 14	0.334
H	6, 11, 14	0.0368

Table 5: this table displays the organization of PA sensors into < 4 km diameter neighbor groups and the P values generated from an ANOVA test conducted on the monitor data within each of the neighborhoods.

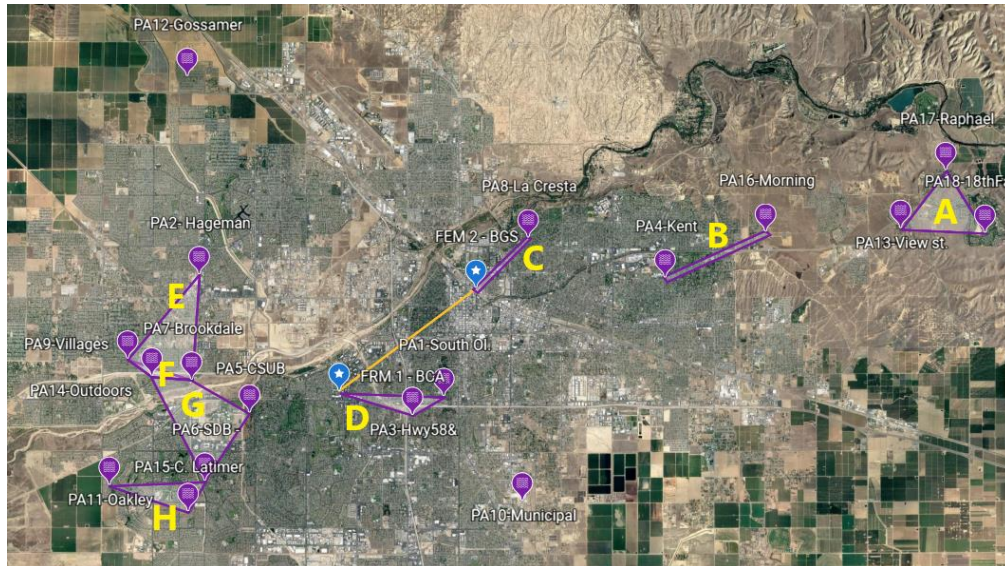


Figure 9: This figure presents the Bakersfield PA sensors as they are grouped into neighborhoods that have a diameter of less than 4 km. This figure was captured from Google Maps after mapping data from PurpleAir and CARB.<sup>23, 24, 25</sup>

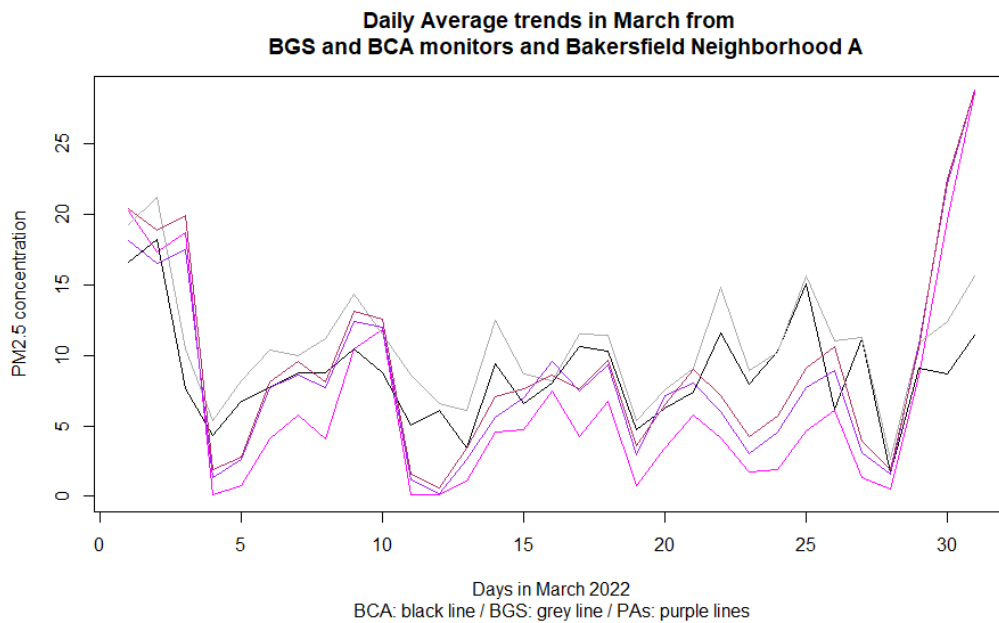


Figure 10: This figure presents daily PM<sub>2.5</sub> µg/m<sup>3</sup> measurements over time (March 2022) for the Bakersfield FEM and FRM monitors, and the 3 PA Sensors in neighborhood A. The purple, maroon, and magenta lines representing the PA monitor measurements are more in agreement than the black and grey lines, representing the FRM and FEM monitors respectively. All

the lines register similar peaks and dips in PM<sub>2.5</sub> measurements, however, likely due to the distance of 11.5-13.8 miles between this neighborhood and the FEM and FRM, there is not as much agreement in comparison to other neighborhoods.

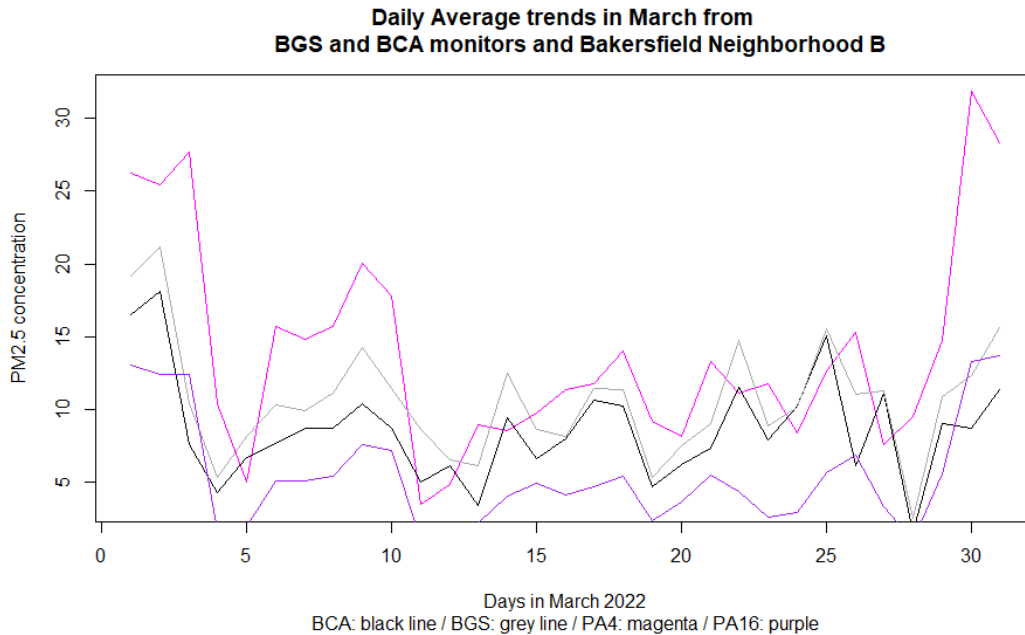


Figure 11: This figure presents daily PM<sub>2.5</sub> μg/m<sup>3</sup> measurements over time (March 2022) for the Bakersfield FEM and FRM monitors, and the 2 PA Sensors in neighborhood B. The purple and magenta lines representing the PA monitor measurements are not in agreement with each other or the black and grey lines, representing the FRM and FEM monitors respectively. However, all the lines register similar peaks and dips in PM<sub>2.5</sub> measurement.

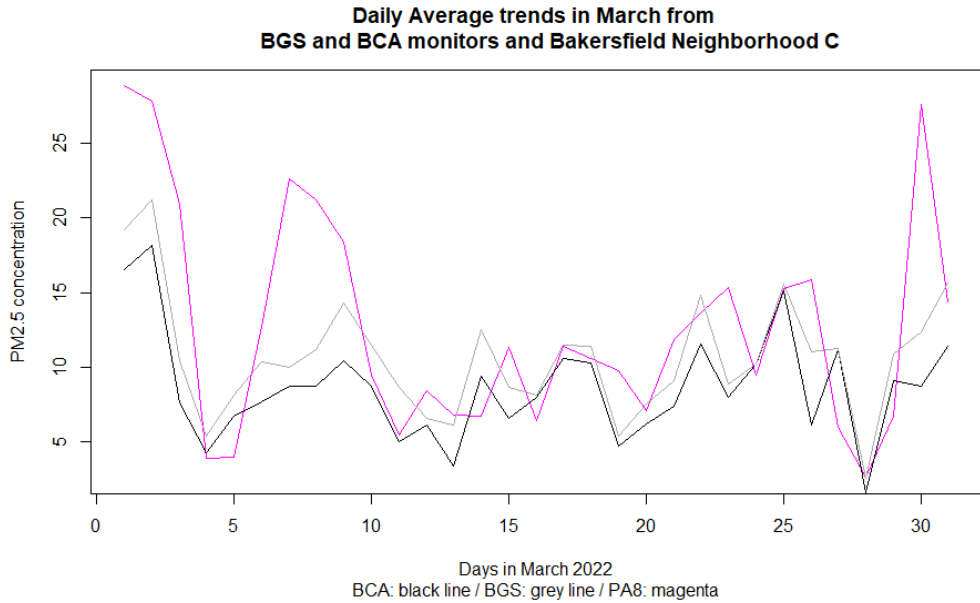


Figure 12: This figure presents daily PM<sub>2.5</sub> μg/m<sup>3</sup> measurements over time (March 2022) for the Bakersfield FRM monitor, and the PA Sensor and BGS (FEM) monitor making up neighborhood C. The magenta line represents the PA monitor measurements that, except for overestimations at high levels of PM<sub>2.5</sub>, closely track the grey BGS line. All the lines register similar peaks and dips in PM<sub>2.5</sub> measurement.

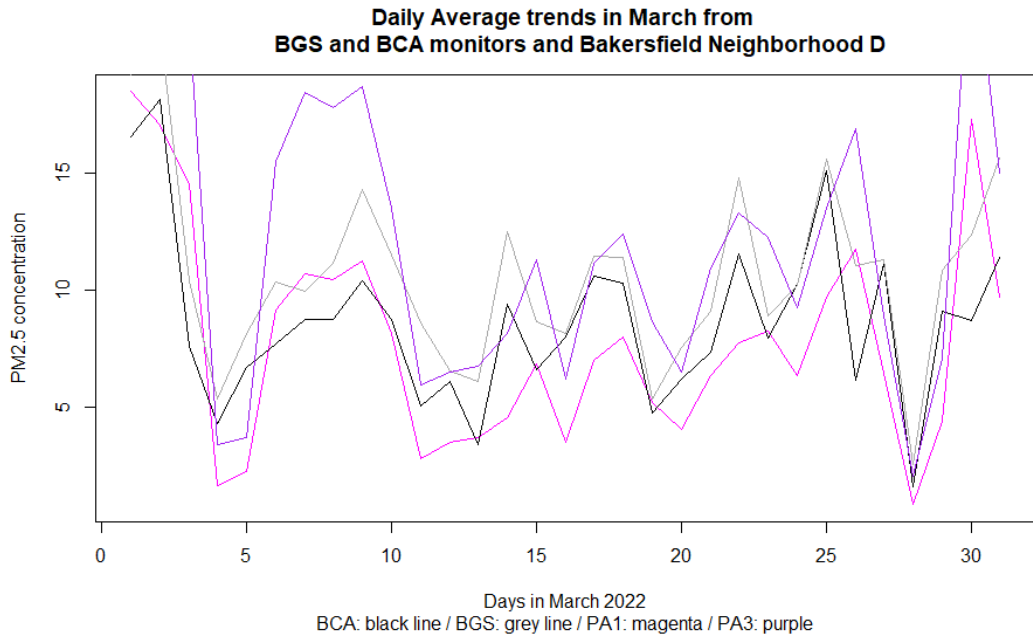


Figure 13: This figure presents daily PM<sub>2.5</sub> µg/m<sup>3</sup> measurements over time (March 2022) for the Bakersfield FEM and FRM monitors, and the 2 PA Sensors in neighborhood D. The purple and magenta lines representing the PA monitor measurements are not in agreement with each other or the black and grey lines, representing the FRM and FEM monitors respectively. However, all the lines register similar peaks and dips in PM<sub>2.5</sub> measurement.

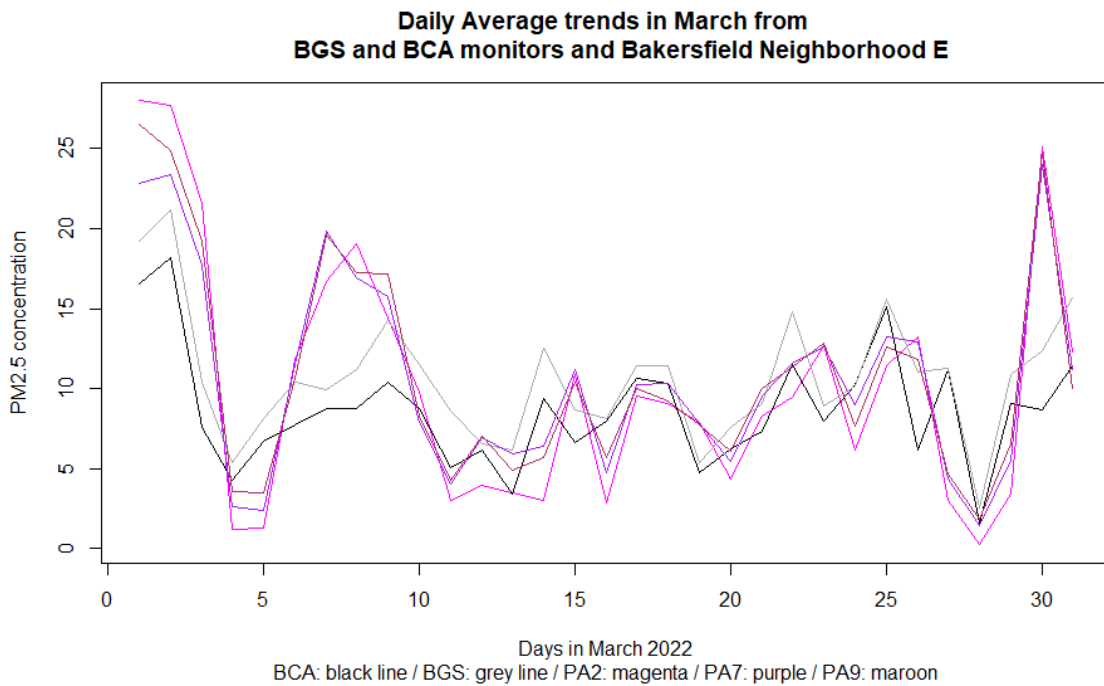


Figure 14: This figure presents daily PM<sub>2.5</sub> µg/m<sup>3</sup> measurements over time (March 2022) for the Bakersfield FEM and FRM monitors, and the 3 PA Sensors in neighborhood E. The purple, maroon, and magenta lines representing the PA monitor measurements are more in agreement than the black and grey lines, representing the FRM and FEM monitors respectively. All the lines register similar peaks and dips in PM<sub>2.5</sub> measurements. Again, the overestimation at high PM<sub>2.5</sub> levels and underestimation at lower levels is observed.

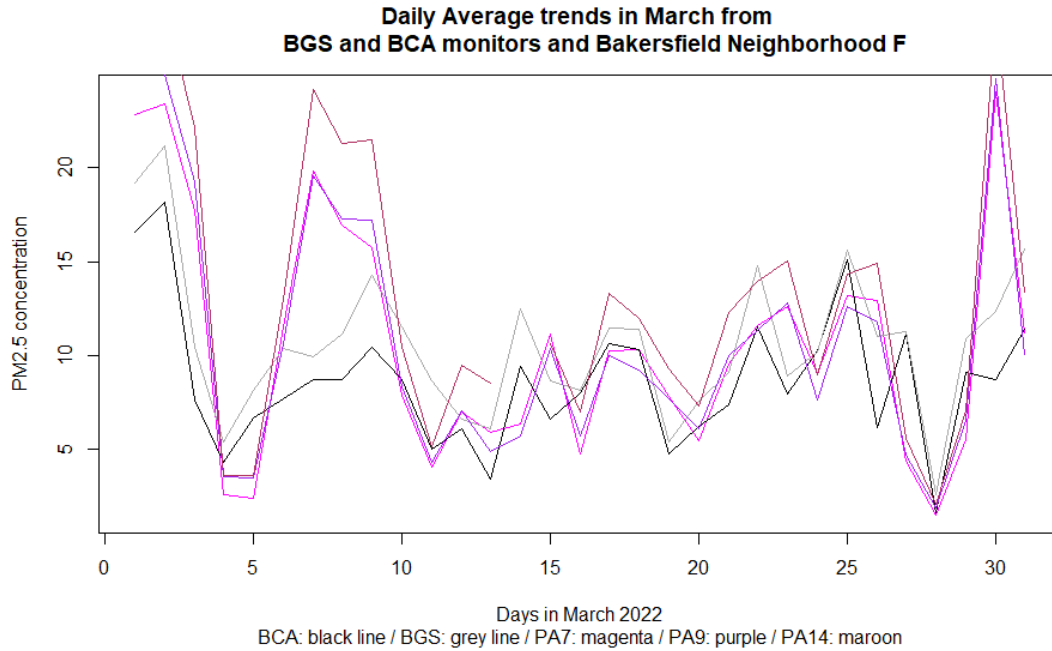


Figure 15: This figure presents daily  $PM_{2.5}$   $\mu g/m^3$  measurements over time (March 2022) for the Bakersfield FEM and FRM monitors, and the 3 PA Sensors in neighborhood F. The purple, maroon, and magenta lines representing the PA monitor measurements are more in agreement than the black and grey lines, representing the FRM and FEM monitors respectively. All the lines register similar peaks and dips in  $PM_{2.5}$  measurements. Again, the overestimation at high  $PM_{2.5}$  levels is observed.

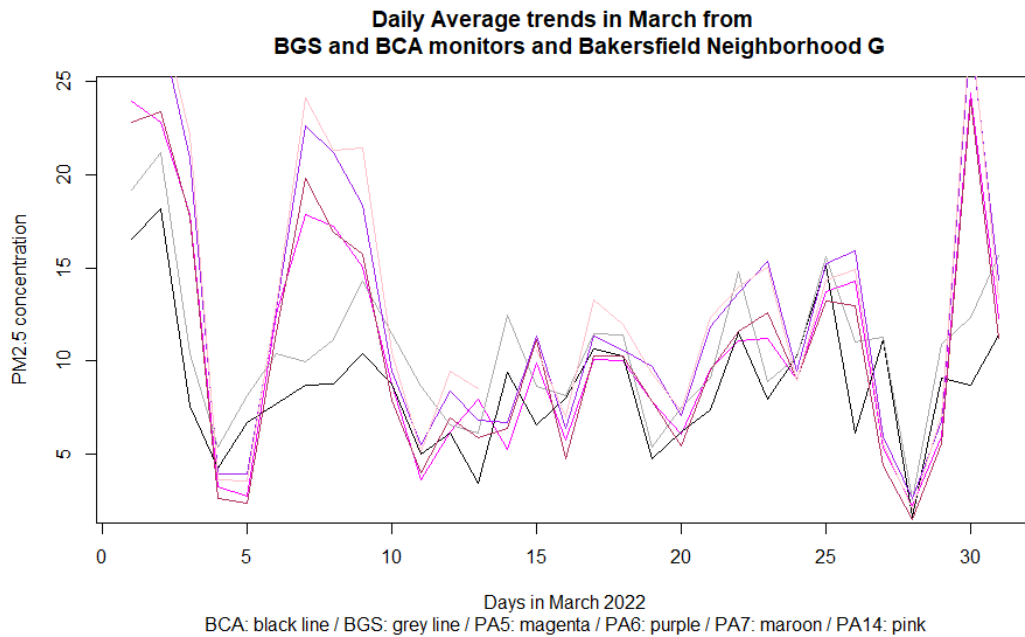
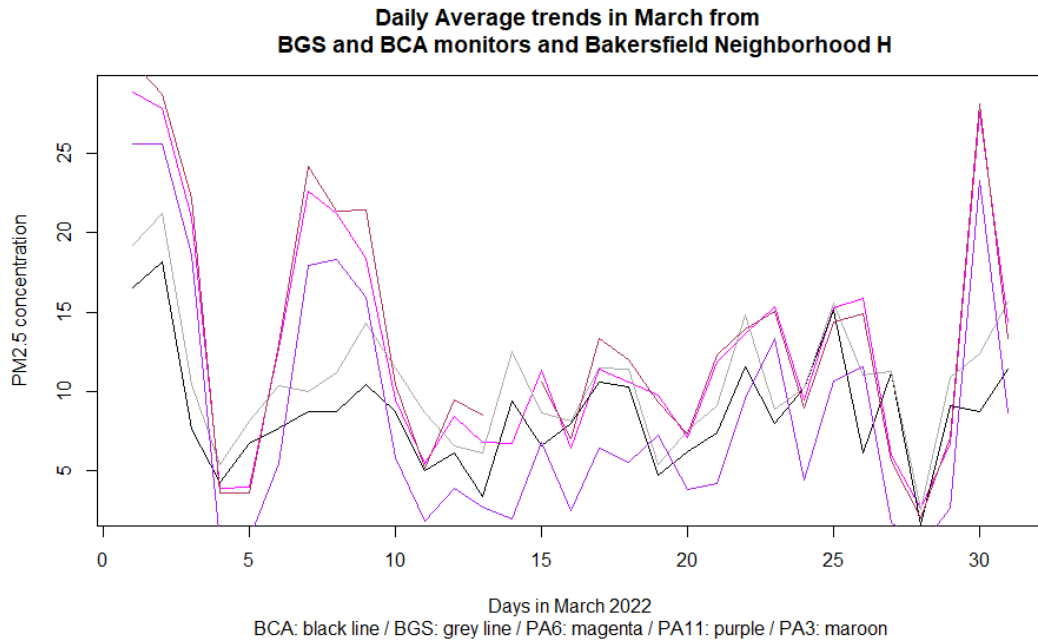


Figure 16: This figure presents daily  $PM_{2.5}$   $\mu g/m^3$  measurements over time (March 2022) for the Bakersfield FEM and FRM monitors, and the 4 PA Sensors in neighborhood F. The purple, maroon, pink, and magenta lines representing the PA monitor measurements are more in agreement than the black and grey lines, representing the FRM and FEM monitors respectively. All the lines register similar peaks and dips in  $PM_{2.5}$  measurements. Again, the overestimation at high  $PM_{2.5}$  levels is observed.



*Figure 17: This figure presents daily PM<sub>2.5</sub> µg/m<sup>3</sup> measurements over time (March 2022) for the Bakersfield FEM and FRM monitors, and the 3 PA Sensors in neighborhood H. The maroon and magenta lines representing the PA3 and PA6 monitor measurements are more in agreement with each other than with the PA11, FRM, or FEM monitor representative lines. Though, all the lines register similar peaks and dips in PM<sub>2.5</sub> measurements. Again, the overestimation at high PM<sub>2.5</sub> levels is observed among all PA monitors.*

### *Sources of Error.*

There are assumptions built into this project that are potential sources of error. Regarding both stages of the project, it is assumed that the FEM and FRM monitors, and PA sensors used in this project are appropriately calibrated and did not experience irregular malfunctions during the period from which data was taken. FEM and FRM monitors were used to represent the baseline value of comparison for the PA because these are the only values currently acknowledged by government agencies. Therefore, errors in measurement by these units, would potentially invalidate any comparison to PA sensors.

There is also the possibility that any discrepancies in recorded PM<sub>2.5</sub> values from certain monitors would be explained by unaccounted PM<sub>2.5</sub> emissions sources. For example, in Bakersfield's neighborhood B (containing PAs 4 and 16), it was recorded that PA4 was only in the proximity of residential sources of emission and that PA16 was in the proximity of both residential and powerplant emissions. However, PA4 is the monitor that consistently records higher PM<sub>2.5</sub> levels. This could be due to an unidentified source of emission close to PA4.

The time frame (the month of March 2022) in which data was gathered from was chosen to lessen the impact of certain known influences on PA sensors and FEM and FRM monitors. A major influence on PM<sub>2.5</sub> levels and PA measurements that this project wanted to avoid was the fire season in California. This decision was based on the difference between the PA and BAM's ability to calculate density. PAs are only able to measure PM<sub>2.5</sub> volume and must estimate the

mass to calculate  $PM_{2.5}$  density. However, FRM and FEM monitors can measure both mass and volume of the  $PM_{2.5}$ , enabling more accuracy in calculating density. Fire particulate matter typically has a lower mass than the PM that PAs are calibrated to measure. Therefore, the accuracy of PA readings will be more significantly impacted than the FEM and FRM readings during these fire events. Since the goal of the project is to determine the ability of PA sensors to detect air quality measurements associated with fossil fuels, and not fires, this project would like to avoid discrepancies in PA data related to fire PM readings. However, taking measurements during the month of March does not completely negate the possibility of fire PM impacting this comparison. There is the possibility of off-season fires and controlled burns.

In addition to the discrepancies that can occur due to particle density, metrological conditions that include factors such as wind speed and direction, relative humidity (RH), and temperature can influence PA measurements as well.<sup>6</sup> The impact that temperature has on PA measurements was another reason that March was chosen, due to it being a relatively temperate month in California.

The placement of PA sensors, relative to structures and the ground, will also likely vary from sensor to sensor, while the placement of FRM and FEM monitors will be done according to regulatory requirements. This type of discrepancy in placement could be the reason behind PA sensors within neighborhoods registering consistently lower or higher levels of  $PM_{2.5}$ , as we see with Bakersfield's PA11 in Neighborhood H (Figure 17). Beyond the careful placement of FEM and FRM monitors, they are also regularly maintained, unlike PA monitors. These situational influences introduce sources of bias that must be considered.

## **Conclusion and Future Directions**

Going back to the objective of the project, based on the discovered patterns, it has been concluded that PA sensors are able to display representative  $PM_{2.5}$  levels for neighborhood-scale areas exposed to pollution from  $PM_{2.5}$  sources. The analysis of PA sensors and a FEM monitor in Livermore, CA reveal patterns that were also seen in the metropolitan area of Bakersfield, CA. First, it was discovered that there are unique  $PM_{2.5}$  levels between neighborhoods. It was also observed that PA measurements tend to overestimate  $PM_{2.5}$  concentrations at higher levels. However, both PA sensors and FEM and FRM monitors register distinguishing parallel peaks and dips in  $PM_{2.5}$  measurements across neighborhoods.

Going forward, there are opportunities to improve and expand upon the results of this project. First, the analysis of PA efficiency, on the urban neighborhood scale, would benefit from repeated analysis in alternate locations and for different periods of time. Through further validation of these low-cost PA sensors, confidence in these measurements encourages greater investment in expanding the PA network. This would then open the door for fine-scale analysis of communities across the globe. As a top priority, an expanded PA network would help tackle the correlation between environmental justice instances and the urban neighborhoods that experience hazardous levels of  $PM_{2.5}$ .

## **Auspices**

This research was supported in part by an appointment to the Mickey Leland Energy Fellowship Program, sponsored by the U.S. Department of Energy and administered by the Oak Ridge Institute for Science and Education.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

## References

1. *Key findings: State of the Air*. State of the Air | American Lung Association. (n.d.). Retrieved July 20, 2022, from <https://www.lung.org/research/sota/key-findings>
2. *San Joaquin valley air pollution control district 2020 air monitoring ...* (n.d.). Retrieved July 21, 2022, from <https://www.valleyair.org/aqinfo/Docs/2020-Air-Monitoring-Network-Assessment.pdf>
3. Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., ... & Forouzanfar, M. H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, 389(10082), 1907-1918.
4. Ling, S. H., & van Eeden, S. F. (2009). Particulate matter air pollution exposure: role in the development and exacerbation of chronic obstructive pulmonary disease. *International journal of chronic obstructive pulmonary disease*, 4, 233.
5. *California Air Resources Board*. Inhalable Particulate Matter and Health (PM2.5 and PM10) | California Air Resources Board. (n.d.). Retrieved July 20, 2022, from <https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health>
6. Ardon-Dryer, K., Dryer, Y., Williams, J. N., & Moghimi, N. (2020). Measurements of PM 2.5 with PurpleAir under atmospheric conditions. *Atmospheric Measurement Techniques*, 13(10), 5441-5458.
7. Environmental Protection Agency. (n.d.). *Power Plants and Neighboring Communities*. EPA. Retrieved July 20, 2022, from <https://www.epa.gov/airmarkets/power-plants-and-neighboring-communities>
8. *Fine Particles (PM 2.5) Questions and Answers*. Department of Health. (n.d.). Retrieved July 21, 2022, from [https://www.health.ny.gov/environmental/indoors/air/pm2\\_5\\_a.htm](https://www.health.ny.gov/environmental/indoors/air/pm2_5_a.htm)
9. Gonzalez, D. J., Francis, C. K., Shaw, G. M., Cullen, M. R., Baiocchi, M., & Burke, M. (2022). Upstream oil and gas production and ambient air pollution in California. *Science of The Total Environment*, 806, 150298.
10. Watson, J. G., Tropp, R. J., Kohl, S. D., Wang, X., & Chow, J. C. (2017). Filter processing and gravimetric analysis for suspended particulate matter samples. *Aerosol Science and Engineering*, 1(2), 93-105.
11. *PurpleAir: Real-time air quality monitoring*. PurpleAir, Inc. (n.d.). Retrieved July 21, 2022, from <https://www2.purpleair.com/>
12. *Most polluted cities: State of the Air*. State of the Air | American Lung Association. (n.d.). Retrieved July 21, 2022, from <https://www.lung.org/research/sota/city-rankings/most-polluted-cities>

13. Plumer, B., & Jucevic, A. (2022, July 7). *Quitting oil income is hard, even for states that Want Climate Action*. The New York Times. Retrieved July 21, 2022, from <https://www.nytimes.com/2022/07/07/climate/california-fossil-fuel-tax-revenue.html>
14. *Air Quality in the san joaquin valley*. firsttuesday Journal. (2016, May 23). Retrieved July 21, 2022, from <https://journal.firsttuesday.us/air-quality-in-the-san-joaquin-valley/52798/>
15. *List of Designated Reference and Equivalent Methods*. (n.d.). Retrieved July 21, 2022, from [https://www.epa.gov/system/files/documents/2022-06/designated\\_reference\\_and\\_equivalent\\_methods\\_-\\_06152022.pdf](https://www.epa.gov/system/files/documents/2022-06/designated_reference_and_equivalent_methods_-_06152022.pdf)
16. Met One Instruments. (n.d.). *BAM 1022 Manual*. Retrieved from <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwi0jOr1oor5AhVoAzQIHebTDysQFnoECAwQAQ&url=https%3A%2F%2Fmetone.com%2Fwp-content%2Fuploads%2F2020%2F02%2FBAM-1022-9805-Operation-Manual-Rev-C.pdf&usg=AOvVaw1EMdIhlGk1I-WzTgfBxBwn>.
17. *About PurpleAir*. PurpleAir, Inc.. (n.d.). Retrieved July 21, 2022, from <https://www2.purpleair.com/community/faq#hc-how-do-purpleair-sensors-compare-to-regulatory-particulate-matter-sensors>
18. *AQMIS data - Kern County*. California Environmental Protection Agency Air Resources Board. (n.d.). Retrieved July 21, 2022, from [https://www.arb.ca.gov/aqmis2/display.php?param=PM25HR&units=001&year=2022&mon=3&day=1&hours=morning&county\\_name=15-Kern&basin=--AIR%2BBASIN--&latitude=--PART%2BOF%2BSTATE--&report=HVAL&order=basin%2Ccounty\\_name%2Cs.name&submit=Retrieve%2BData&ptype=aqd&std15=](https://www.arb.ca.gov/aqmis2/display.php?param=PM25HR&units=001&year=2022&mon=3&day=1&hours=morning&county_name=15-Kern&basin=--AIR%2BBASIN--&latitude=--PART%2BOF%2BSTATE--&report=HVAL&order=basin%2Ccounty_name%2Cs.name&submit=Retrieve%2BData&ptype=aqd&std15=)
19. San Joaquin Valley Air Pollution Control District. (n.d.). (rep.). *2020 Air Monitoring Network Plan*. Retrieved from <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwJxncGRqIr5AhUDIX0KHaS8DTAQFnoECAsQAQ&url=https%3A%2F%2Fwww.vall eyair.org%2Ffaqinfo%2FDocs%2F2017-Air-Monitoring-Network-Plan.pdf&usg=AOvVaw0C-D8wPxXvxX7dXwR4OOiT>.
20. *Air Quality System (AQS) monitors*. ArcGIS Hub. (n.d.). Retrieved July 22, 2022, from <https://hub.arcgis.com/datasets/4f4a2cbd49c64a80813c82a82fcfb729/explore?layer=14&location=31.783687%2C-97.734000%2C3.99&showTable=true>
21. *Oil & Gas Research and Visualization Tool*. Research our oil & gas production database. (n.d.). Retrieved July 22, 2022, from <https://www.shalexp.com/map?a1=on&f1=county&c1=contains&v1=Kern&a2=on&f2=oil&c2=greater&v2=0&ay=30.788778498652345&ax=-127.54837890625&zy=38.61663557601264&zx=-108.87162109375&zoom=7>
22. *Spearman's correlation*. www.statstutor.ac.uk. (n.d.). Retrieved July 22, 2022, from <https://statstutor.ac.uk/resources/uploaded/spearmans.pdf>

23. Google. (n.d.). *Bakersfield, California*. Google earth. Retrieved July 22, 2022, from <https://earth.google.com/web/@35.35633765,-119.0627655,116.52754508a,18958.22168057d,35y,0h,0t,0r>
24. *Real-time air quality map*. PurpleAir. (n.d.). Retrieved July 22, 2022, from <https://map.purpleair.com/1/mAQI/a10/p604800/cC0#10.82/35.339/-119.0476>
25. Carb Pollution Mapping Tool. (n.d.). Retrieved July 22, 2022, from [https://www.arb.ca.gov/ei/tools/pollution\\_map/v30beta.htm](https://www.arb.ca.gov/ei/tools/pollution_map/v30beta.htm)
26. *California Power Plants*. California Energy Commission. (n.d.). Retrieved July 22, 2022, from [https://cecgis-caenergy.opendata.arcgis.com/datasets/4a702cd67be24ae7ab8173423a768e1b\\_0/explore?filters=eyJDb3VudHkiOlsiS2VybiJdLCJQcmIFbmVvZ3lTb3VyY2UiOlsiTkciXX0%3D&location=35.419598%2C-119.241859%2C10.00](https://cecgis-caenergy.opendata.arcgis.com/datasets/4a702cd67be24ae7ab8173423a768e1b_0/explore?filters=eyJDb3VudHkiOlsiS2VybiJdLCJQcmIFbmVvZ3lTb3VyY2UiOlsiTkciXX0%3D&location=35.419598%2C-119.241859%2C10.00)

