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Spatio-Temporal Analysis of Roadside Transportation-Related Air Quality (StarTraq 2021): A Characterization of Bike Trails and Highways in the Fresno/Clovis Area

Jaymin Kwon, PhD Yushin Ahn, PhD Steve Chung,PhD

California State University Transportation Consortium

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Report 22-48

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16. Abstract

The San Joaquin Valley is identified as an area with a high level of particulate matter (PM) in the air, reaching above the federal and state clean air standards (EPA 2019). Many of the cities in the valley are classified as the most polluted cities in the United States for both particulate matter and ozone pollution (American Lung Association, 2021). To resolve this issue, alternative forms of transportation have been considered in transportation planning. In this study, active transportation mode air quality was monitored on selected Woodward Park and Old Clovis trails and urban bike lanes. Real-time aerosol monitors, and low-cost sensors were carried in a backpack on bicycles during the sampling. Researchers collected GPS data via a portable GPS technology called Tracksticks. Driving transportation mode air quality data was acquired from the roadways within the Fresno/Clovis area, spanning six sampling routes, and during intercity trips between Fresno, Berkeley, and Los Angeles, for a total of five sampling routes. 'On-Road' (outside vehicle) monitors were installed on the roof of a vehicle while 'In-Vehicle' monitors were installed inside the vehicle for comparison with the particulate pollution levels in the two contrasting microenvironments. The results showed the following three main outcomes: (1) clear relationships exist among PMs of different sizes; (2) there were greater variations in air quality of bike trails and On-Road samples than backyard and In-Vehicle samples; (3) we observed significant differences in air quality inside and outside the vehicle while driving local and intercity roadways; and (4) the road trip to the Bay area revealed that San Joaquin Valley has increased ambient PM2.5 and black carbon (BC) levels compared to those in the Bay Area on every trip, regardless of the daily change of the air quality.

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Contents

Acknowledgments vi

List of Figures.. viii

List of Tables...x

Executive Summary 1

1. Introduction.. 3

2. Methodology.. 5

2.1 Data and its acquisition: Air quality sampling 5

2.2 Data and its acquisition: Camera-assisted visual data.. 7

2.3 Time series and spatial data processing... 7

3. Results and Discussion.. 11

3.1 Collocation air quality measurement for Instrument Calibration 11

3.2 Camera assisted visual data.. 13

3.3 Air quality on bike trails Active transportation mode... 17

3.4 Air quality On-Road and In-Vehicle in the Fresno Area.. 25

3.5 Air quality On-Road and In-Vehicle during intercity trips....................................... 32

4. Summary & Conclusions 45

Bibliography 47

About the Authors.. 49

List of Figures

Figure 1. Screenshot of the Telemetry Extractor, a Web-Based Trajectory Extraction Algorithm 8

Figure 2. Illustration of the GPX Structure in MATLAB........ 9

Figure 3. Collocation Data for PM_{10}, $PM_{2.5}$, PM_1, and BC for Calibration........ 11

Figure 4. Linear Regression of Aerosol Monitoring Sensors 12

Figure 5. A panoramic View of GoPro Max360........ 13

Figure 6. A View of GoPro Hero 9........ 14

Figure 7. An Illustration of Vehicle Detection 14

Figure 8. BC concentration measured On-Road During an Intercity Trip between Fresno and Berkeley on 11/23/2021 15

Figure 9. Example Peak 6 of BC Measured On-Road 11/24/2021 Highway 99 Northbound to Berkeley 16

Figure 10. Example Peak 10 of BC Measured On-Road 11/24/2021 Highway 99 Southbound to Fresno. 17

Figure 11. Time Series Plot, Concentration Heat Maps, and Box and Whisker Plots for BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on Bike Trails, and in the Backyard on 9/19/21 19

Figure 12. Time Series Plot, Concentration Heat Maps, and Box and Whisker Plots for BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on Bike Trails, and in the Backyard on 9/23/21 21

Figure 13. Time Series Plot, Concentration Heat Maps, and Box and Whisker Plots for BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on Bike trails and in the Backyard on 10/19/21 23

Figure 14. The Box and Whisker Plots for BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on Bike Trails and in the Backyard on 8/31/21 and 9/17/21........ 24

Figure 15. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on 4/4/21 27

Figure 16. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on 4/6/21 28

Figure 17. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on 12/21/21 29

Figure 18. The Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) in the Fresno Area on 4/3/21, 4/5/21, and 9/25/21 31

Figure 19. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on 11/24/21 (F-B-F Trip 1) 34

Figure 20. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) on 11/27/21 36

Figure 21. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) during the Fresno to Berkeley Trip on 12/23/21 38

Figure 22. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) during the Fresno-Los Angeles Trip on 12/26/21 40

Figure 23. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) during the Fresno-Berkeley Trip on 1/12/22 42

LIST OF TABLES

Table 1. Description of the Air Quality Samples 6

Table 2. GoPro Hero 9 and Max 360 Models 7

Table 3. An Example of Time-Synchronized Data 10

Table 4. Summary Statistics of $PM_{2.5}$ and BC Concentrations (μg/m^3) on Bike Trails and in the Backyard 18

Table 5. Summary Statistics of the On-Road and In-Vehicle $PM_{2.5}$ and BC Concentrations (μg/m^3) in the Fresno Area 26

Table 6. Summary Statistics of the $PM_{2.5}$ and BC Concentrations (μg/m^3) of Inter-city Trip 33

Executive Summary

Many cities are concerned with air pollution as it is a threat to their public health, and reducing carbon emissions from automobiles has been a central challenge for several decades. To resolve this issue, alternative forms of transportation have been considered in transportation planning. In this research, we attempt to provide insightful information that can be used for planning and promoting alternative transportation. This work is an extension of the StarTraq 2020 project that was funded by the Fresno State Transportation Institute (FSTI). The research broadens the scope of roadside, on-road, and in-vehicle air quality data from particle pollutants to understand the spatio-temporal aspects of particulate matter in various environments, and, hopefully, this will deepen our understanding of the mode of transportation impacts air quality.

In order to examine the spatio-temporal variation in transportation-related air quality, data was collected from bike trails, local roadways, and intercity roads. Active transportation mode air quality was monitored on selected Woodward Park and Old Clovis trails and urban bike lanes. Real-time aerosol monitors, and low-cost sensors were carried in a backpack on bicycles during the sampling. Researchers collected GPS data via a portable GPS technology called *Tracksticks*. Driving transportation mode air quality data was acquired from the roadways within the Fresno/Clovis area along six sampling routes, and during the intercity trips from Fresno, Berkeley, and Los Angeles which consisted in five sampling routes. 'On-Road' (outside vehicle) monitors were installed on the roof of the vehicle while 'In-Vehicle' monitors were installed inside the vehicle to compare the particulate pollution levels in two contrasting microenvironments. Tracksticks logged the GPS data for all routes. Before and after the driving, researchers performed collocation for any offsets or drifts of air monitors for quality assurance and quality control (QA/QC).

As results of this work, we list the following key findings from exploratory data analysis.

- Since certain particulate matter (PM) concentrations, namely PM_{10} and PM_1 concentrations, were nearly identical to $PM_{2.5}$ concentrations, the majority of PM near roadways consisted in smaller particles, and this may indicate that the particles are from combustion sources or secondary aerosol production.

- We observed that the particle concentrations were more varied in the bike trails and on-road samples than backyard and in-vehicle samples.

- The average In-Vehicle $PM_{2.5}$ was 31% of the average On-Road $PM_{2.5}$, while the average In-Vehicle black carbon (BC) concentration was 5.5% of the average On-Road BC when local and intercity data were combined.

- The average On-Road $PM_{2.5}$ concentration was 2.9 times higher than that of In-Vehicle $PM_{2.5}$ from the Fresno roadway. The average On-Road $PM_{2.5}$ concentration was 4.3 times higher than that of In-Vehicle $PM_{2.5}$ on intercity trips. The average On-Road BC concentration was 65 times higher than that of In-Vehicle BC from the Fresno roadway. The average On-Road BC concentration was 62 times higher than that of In-Vehicle BC on intercity trips.

- The PM concentrations measured On-Road on trips to the Bay Area demonstrated that the San Joaquin Valley has increased ambient PM2.5 and BC compared to those in the Bay Area, regardless of the daily change in air quality.

- For our measurement, PM2.5 was 21% higher than that of FRM on average for all types of samples consistently. Black carbon data was not obtained from FRM.

It is evident that active transportation can improve urban air quality and public health. The planning of safer bike trails can significantly reduce the active transportation users' exposure to those air pollutants. The air pollution control district provides accurate real-time air quality of PM in the area to the public. However, there is a big knowledge gap in the information on black carbon and other toxic components of PM that are emitted from internal combustion engine vehicles.

In this research, we have collected air quality data from transportation-emitted particulate matter including PM_{10}, $PM_{2.5}$, PM_1, BC, and PAHs. These particulate pollutants were measured concurrently in different transit modes and microenvironments, including bike trails, On-Road, In-Vehicle, local, and intercity environments to understand the contribution of immediate roadway emissions to personal exposure. In the near future, we will collect geographical information system (GIS) data and visual data from cameras. These different types of data will enable us to investigate further into spatio-temporal data analysis, and to identify the emission source.

1. Introduction

The San Joaquin Valley, and Fresno in particular, are identified as areas with levels of particulate matter that go above federal and state clean air standards (EPA 2019). Many of the cities in the eight-county region, including 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 with a diameter of 2.5 micrometers ($PM_{2.5}$), is known to pose a risk to human health. While many $PM_{2.5}$ particles vary in composition, black carbon (BC), which occurs due to incomplete combustion from gas and diesel engines, makes up most of the particulate matter emitted worldwide (Bessagnet & Allemand 2020). Black carbon and polycyclic aromatic hydrocarbons (PAH) emitted from fossil fuel combustion, mainly from transportation mobile sources, are associated with increased health complications, including high levels of hospital admission, emergency room visits linked to asthma, increased cardiovascular disease risks, and even premature death (Noth et al. 2011).

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. A study found correlations among ambient particulate matter concentrations, asthma prevalence, and hospitalizations (Alcala et al. 2019). Other studies in the San Joaquin Valley have shown that mothers exposed to elevated levels of 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, which is 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), which can also decrease quality of life. The pollutants that occur near these roads depend on traffic, temperature, and wind (Baldauf et al. 2009).

Active transportation modes, such as bike riding and walking, and easy access to transit in communities, require consolidation of data-driven transportation information. This information is critical to the stakeholders and public. Such relevant and timely information based on data can facilitate decision-making processes for establishing public policy, and urban planning for sustainable growth and promoting public health. The Centers for Disease Control and Prevention (CDC) defines 'active transportation' as the human-powered mode of transportation (CDC 2011). Active transportation is directly related to access to safe and comfortable sidewalks and bikeways. The United States Department of Transportation (DOT) describes the benefits of active transportation as follows: (1) reducing obesity and the risks of developing costly chronic conditions such as diabetes; and (2) improving the quality of life for low-income families, minorities, and communities with residents who have no vehicles. There are significant issues with active transportation, such as air pollution, local and regional disparities in environmental properties and social infrastructure or liabilities, and poor dissemination to stakeholders for developing better policies. The previous FSTI StarTraq 2020 project has provided consolidated data-driven transportation information to the public including: (1) transportation-related particle pollution data; (2) spatial analyses of geocoded vehicle emissions; and (3) neighborhood characterization for the built environment. StarTraq 2020 confirms that roadside $PM_{2.5}$, BC, and PAHs were significantly elevated compared to concentrations at the ambient monitoring stations because of immediate source proximity.

The StarTraq 2020 project focused on roadside exposure during walking in Fresno/Clovis neighborhoods. StarTraq 2021 project expanded to another active transportation mode—bike riding. This mode of transportation is still understudied in the Fresno/Clovis area, even though many people use bike trails in the parks and bike lanes for commuting. In promoting alternative forms of transportation, this research provides valuable information on baseline pedestrian and cyclist exposure to air pollution. The bike trail samples were compared to the stationary reference samples collected in a residential backyard. The stationary backyard samples were used to correct the potential drifting of the real-time monitoring data by collocation before and after the bike ride sampling and possible systematic offsets in sensors. To characterize the impact of roadway emissions while driving on local roadways and highways, the sensors were placed inside and outside of the vehicle simultaneously. This parallel monitoring is referred to as In-Vehicle and On-Road, respectively. Camera-assisted visual data collection was established, incorporating geocoded pollution data for spatio-temporal analysis.

2. Methodology

2.1 Data and Its Acquisition: Air Quality Sampling

Particulate matter (PM_{10}, $PM_{2.5}$, and PM_1) and particle-bound BC concentrations were monitored using real-time aerosol monitors, namely the DustTrak DRX II 8533 (TSI, St. Paul, MN), and the microAeth AE51 (AethLab, Berkeley, CA). Active transportation mode air quality was monitored on the Woodward Park and Old Clovis trails and urban bike lanes. The real-time aerosol monitors, and the low-cost sensors were carried in a backpack on the bicycles during the sampling. The GPS data was collected by the application Tracksticks. To provide a baseline for the bike trail air samples, one set of monitors was located in the backyard during bike riding as a reference. Driving transportation mode air quality was monitored from the selected roadways within the Fresno/Clovis area (six samplings), and during the intercity trip from Fresno to and from Berkeley and Los Angeles (five samplings). 'On-Road' (outside vehicle) monitors were installed on the roof of a vehicle, while 'In-Vehicle' monitors were installed inside of the vehicle for a comparison of the particulate pollution levels in two contrasting microenvironments. Tracksticks logged the GPS data for all the trips. Before and after driving, collocation sampling was performed for any offsets or drifts of air monitors for quality assurance (QA) and quality control (QC). There were many days when wildfire smoke affected regional air quality during the study periods. The air monitors were located side by side in the backyard to collect collocation samples for calibration and QA purposes. Variations in individual aerosol monitoring sensors were adjusted using collocation (side-by-side) data for accuracy. Table 1 summarizes the air quality samples in this study.

Table 1. A description of the Air Quality Samples

Air Sample Types	Date	Starting time	Ending time	Duration (HH:MM)	Duration (Minute)
Bike Trail vs. Backyard					
Bike Trails – Woodward Park	8/31/2021	8:50	9:40	0:50	50
Bike Trails – Woodward Park	9/17/2021	11:47	13:26	1:39	99
Bike Trails – Woodward Park	9/19/2021	15:47	18:17	2:30	150
Bike Trails – Woodward Park	9/23/2021	16:28	18:08	1:40	100
Bike Trails – Willow Clovis Trail	10/19/2021	14:50	16:39	1:49	109
On-Road vs. In-Vehicle					
Fresno Roadways	4/3/2021	21:07	22:47	1:40	100
Fresno Roadways	4/4/2021	21:00	22:14	1:14	74
Fresno Roadways	4/5/2021	20:43	21:57	1:14	74
Fresno Roadways	4/6/2021	20:48	22:12	1:24	84
Fresno Roadways	9/25/2021	13:00	14:31	1:31	91
Fresno Roadways	12/21/2021	16:14	19:00	2:46	166
Intercity Trip, Fresno – Berkeley	11/24/2021	9:22	19:10	9:48	588
Intercity Trip, Fresno – Berkeley	11/27/2021	9:57	18:25	8:28	508
Intercity Trip, Fresno – Berkeley	12/23/2021	11:11	20:14	9:03	543
Intercity Trip, Fresno – Los Angeles	12/26/2021	9:38	23:56	14:18	858
Intercity Trip, Fresno – Berkeley	1/12/2022	11:28	20:09	8:41	521
Wildfire Impacted Periods at Backyard	41 days	varies	varies	809:54	48,594

2.2 Data and Its Acquisition: Camera-Assisted Visual data

Visual data was collected using GoPro cameras, recording the surrounding scene with a GPS location while air-pollution data was being collected. The camera system was used in two scenarios: (1) air quality on walking and bike trails to represent active transportation modes; and (2) air quality on highways, arterials, connectors, and local roads to represent In-Vehicle and On-Road exposure for vehicle operators. The cameras used in this research were the GoPro Hero 9 and the GoPro Max 360. Both cameras have built-in GPS and 5K video and image resolution (Table 2).

Table 2. GoPro Hero 9 and Max 360 Models

GoPro Hero 9	GoPro Max 360
CMOS Sensor 23.6 Megapixel Maximum 5120×2880 at 24/25/30 fps 1/25-1/2000 seconds shutter speed GPS 	CMOS Sensor 5k video Maximum 4993×2496 at 25/30 fps 8.9mm focal length Angle of view: 360 degrees GPS 

Note: GoPro Hero 9 and Max 360 Models are used for visual data collection and particulate matter concentrations during transportation.

2.3 Time Series and Spatial Data Processing

Particulate matter concentrations and location data were synchronized based on the timestamps of each type of data using MATLAB. The pollution concentrations were time-weighted averages for minute-long intervals. When there were multiple GPS data points within a minute, the coordinates were averaged to provide a coordinate for one-minute long intervals. GoPro cameras come with built-in GPS and the location at any time can be extracted using GoPro's Telemetry Extractor (https://goprotelemetryextractor.com).

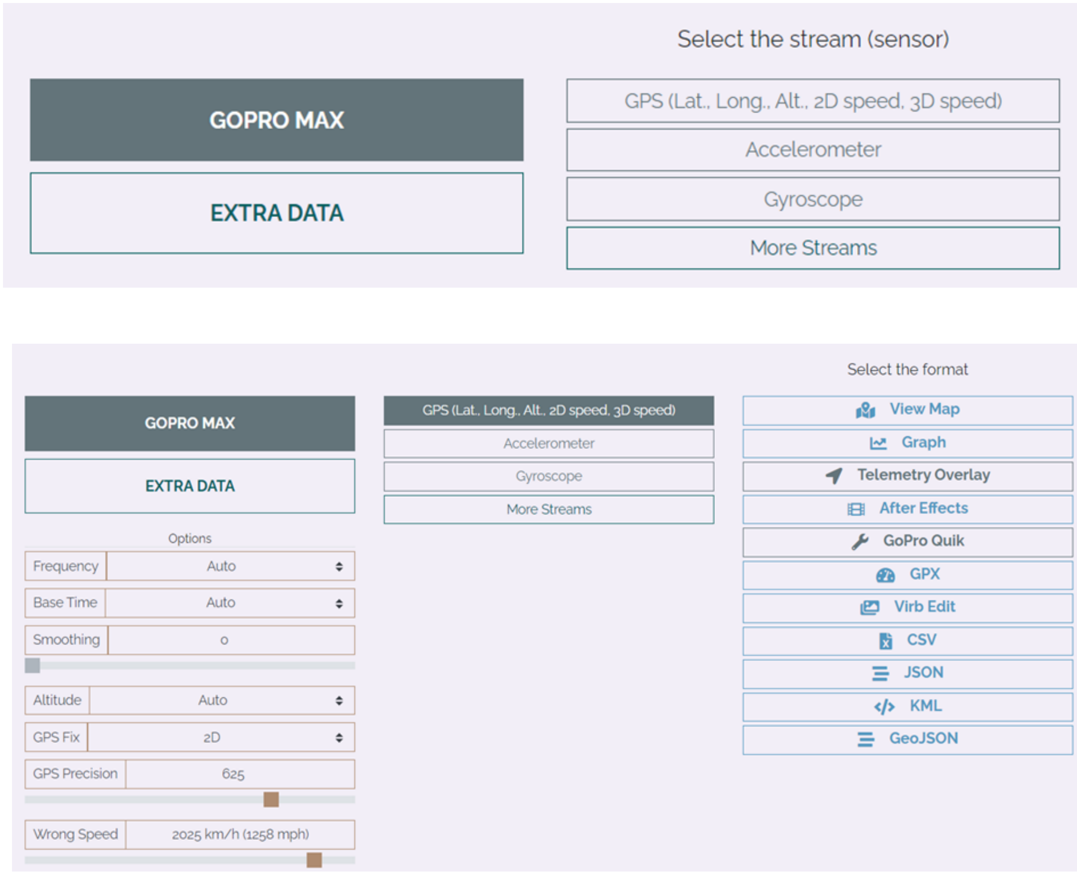

Figure 1. Screenshot of the Telemetry Extractor, a Web-Based Trajectory Extraction Algorithm

Geographic coordinates—latitude, longitude, and altitude—can be extracted and exported to various file types. The output format we used was GPX, an XML-based GPS exchange format file that stores coordinate data. These files describe waypoints, tracks and routes. MATLAB provides the ability to read all the necessary information sourced from the cameras.

```
Collection properties:
    Geometry: 'point'
    Metadata: [1×1 struct]
Feature properties:
    Latitude: [1×4447 double]
   Longitude: [1×4447 double]
   Elevation: [1×4447 double]
        Time: {1×4447 cell}
         Fix: {1×4447 cell}
        HDOP: [1×4447 double]
     Comment: {1×4447 cell}
```

Figure 2. Illustration of the GPX Structure in MATLAB

Figure 2 shows the GPX information: Latitude, Longitude, Elevation in mean sea level, time, and Horizontal dilution of precision (HDOP).

When monitoring air pollution, a dedicated GPS unit, Tracksticks, was deployed along with air pollution sensors, which did not record positional information while the vehicle was not in motion. GoPro GPS can fill those gaps, and provide detailed positional information from its high frame rates.

Air pollution monitoring involves multiple sensors. One-minute intervals are the basic frequency which come from AtmoTubes and Dylos, thus high sampling rates are interpolated to have the same time interval. The sampling time rates for various sensors that were used in field campaigns are summarized as follows.

- GoPro GPS: 20Hz, 1/20 sec.
- Tracksticks GPS: 10 sec.
- GoPro Video: 60 fps, 1/60 sec.
- DRX: 10 sec.
- Dylos: 60 sec.
- AtmoTubes: 60 sec.

Based on GPS Tracksticks, or GoPro GPS, times for other pollution sensors are searched in a GPS one-minute bin. The binned data are averaged to match GPS location data.

Table 3. An Example of Time-synchronized Data

Date	Latitude	Longitude	BC In-Vehicle	BC On-Road	PM2.5 In-Vehicle	PM2.5 On-Road
4/4/2021 21:00	36.88752	-119.74659	0.196	0.239	8.350	8.951
4/4/2021 21:01	36.88768	-119.74661	0.196	0.463	8.736	8.876
4/4/2021 21:02	36.88799	-119.74492	0.161	0.472	8.908	8.651
4/4/2021 21:03	36.88821	-119.74638	0.187	0.274	8.092	8.651
4/4/2021 21:04	36.88993	-119.75349	0.208	0.287	6.933	8.689
4/4/2021 21:05	36.89064	-119.76056	0.160	0.303	6.118	8.839
4/4/2021 21:06	36.88538	-119.76645	0.054	0.376	5.603	8.914
4/4/2021 21:07	36.87770	-119.77156	0.037	0.388	5.131	8.839
4/4/2021 21:08	36.87129	-119.77740	0.016	0.454	4.659	8.689
4/4/2021 21:09	36.86398	-119.78176	0.031	0.703	4.230	8.651
4/4/2021 21:10	36.85731	-119.78618	0.060	0.650	3.929	8.801
4/4/2021 21:11	36.85154	-119.78745	0.033	0.959	3.629	8.914
4/4/2021 21:12	36.84405	-119.78683	0.073	1.056	3.586	9.101
4/4/2021 21:13	36.83806	-119.78770	0.102	0.805	3.414	9.739
4/4/2021 21:14	36.83720	-119.79806	0.048	0.762	3.114	9.514

Note: This table enables statistical analysis of air pollution data in two different microenvironments.

The time-series of multiple pollution concentrations and coordinates in various microenvironments were combined for plots and summary statistics. The box and whisker plots were illustrated for comparison of the distribution. The time series plots illustrated variable pollution by time to identify the location, and potential emission sources, of higher pollution levels. Concentration and location data were used to illustrate the heat maps for each trip.

3. Results and Discussion

3.1 Collocation Air Quality Measurement for Instrument Calibration

The collocation concentrations were measured by multiple monitors side-by-side in the backyard. The height of air inlets was six feet above the ground. There were no significant emission sources located nearby, except the street over the fence. The distance from the samplers to the roadside was twelve meters, and twenty meters to the center of the road.

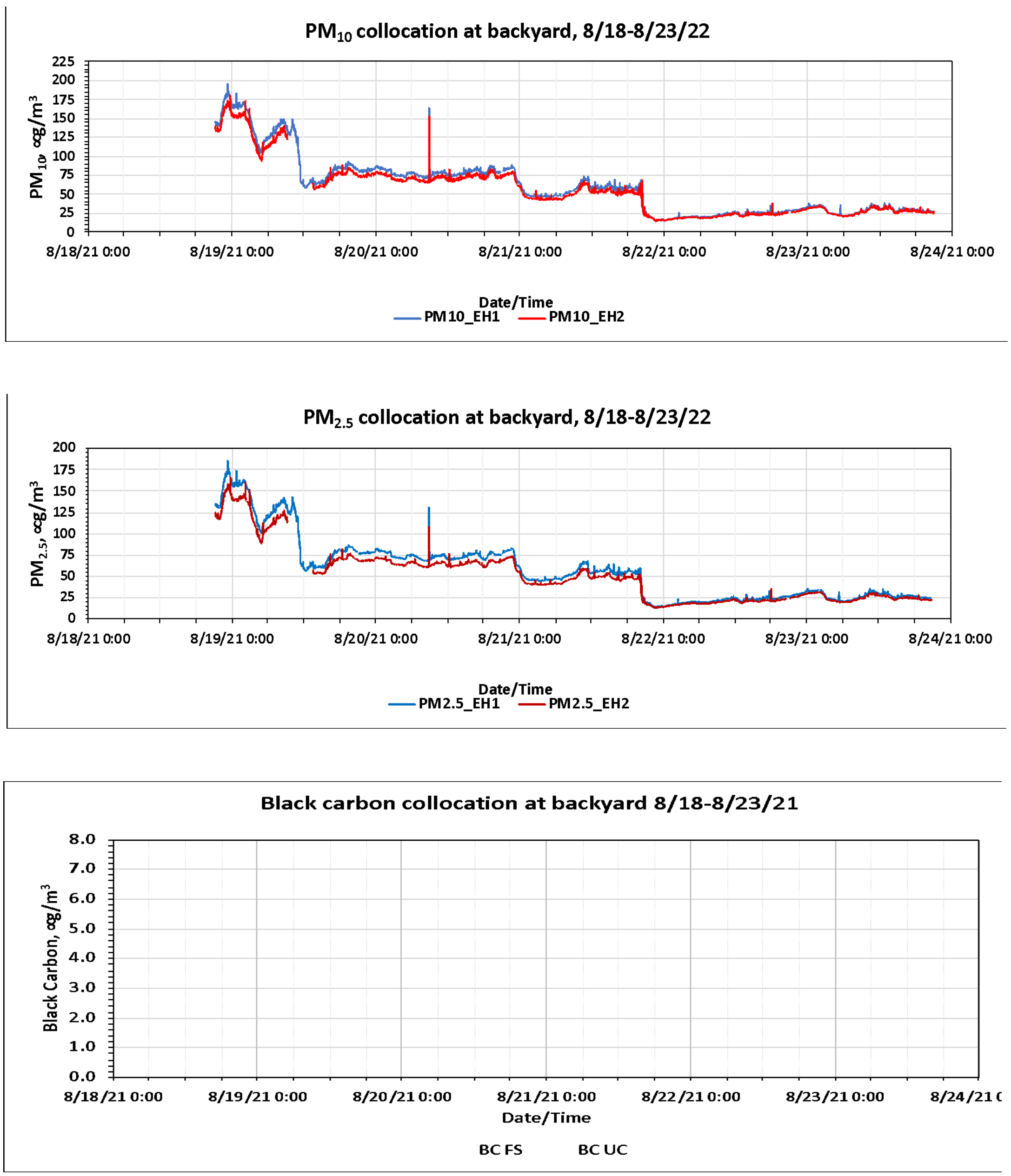

Figure 3. Collocation Data for PM_{10}, $PM_{2.5}$, PM_1, and BC for Calibration

Figure 3 illustrates five-day PM_{10}, $PM_{2.5}$, PM_1, and BC concentrations measured during wildfire-influenced days in August. The concentrations from the two monitors agreed well for PM_{10}, $PM_{2.5}$, and PM_1. BC collocation samples agreed as well, except when there was increased background noise from both sensors after twelve hours from time zero. A high concentration of BC caused the noise. Frequent changing of the filter reduced the noise.

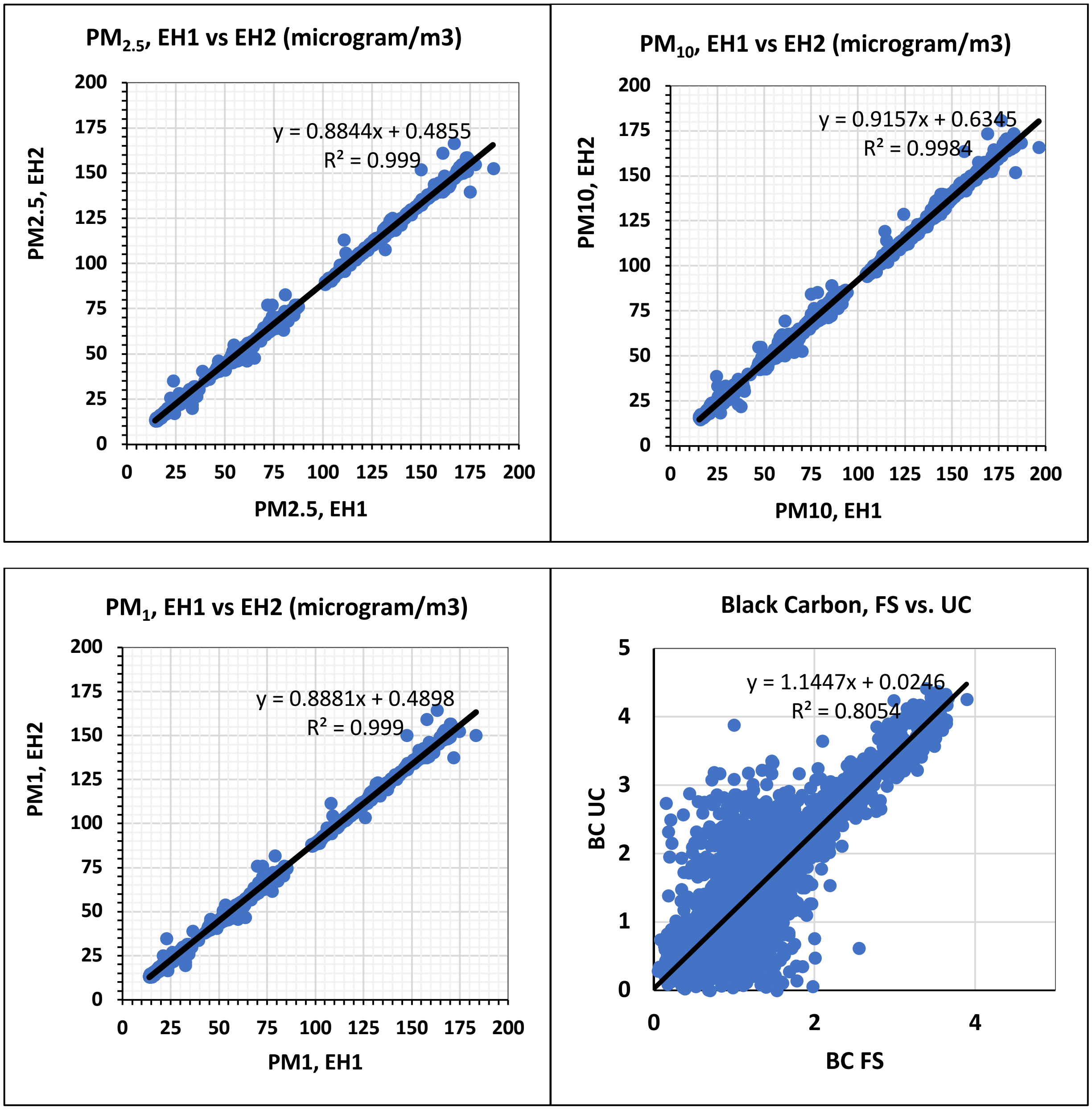

Figure 4. Linear Regression of Aerosol Monitoring Sensors

Figure 4 shows the linear relationship between two sensors for PM_{10}, $PM_{2.5}$, and PM_1. Linear regression models were fitted to examine the relationship. This figure evinces a very strong relationship between EH1 and EH2 units. The coefficients of determination were 0.999, 0.998, and 0.999 for PM_{10}, $PM_{2.5}$, and PM_1, respectively. The coefficient of determination for BC collocation samples (between FS and UC) was high at 0.81. For PM samplers (DustTrak DRX Aerosol Monitors, TSI Inc.), the EH2 unit consistently measured lower than the EH1 unit. The difference between the two units was calculated and used for the correction of each data point. For BC samples, one unit (microAeth UC) measured consistently higher than the other unit (microAeth FS). The difference between the two sensors was calculated and corrected for an accurate comparison of the separate units. Further calibration includes (1) gravimetric conversion of PM concentrations; and (2) unit conversion from mg/m^3 and ng/m^3 to $\mu g/m^3$ of air for PM and BC, respectively.

3.2 Camera-Assisted Visual Data

One of the key features in this study is the incorporation of a camera system along with air pollution sensors. Video from this system provides information on the conditions of the road, traffic, land use, weather, etc. Figure 5 shows a 360-degree panoramic view from the GoPro Max360 when mounted on top of a helmet in a bike trail field campaign. Figure 6 shows an image from a GoPro Hero 9 camera. Depending on the field of view mode, it can provide a super-wide 155-degree field of view which covers most of the front view. Figure 7 illustrates how vehicles are detected using the MATLAB deep learning toolbox. The algorithm uses a trained Faster R-CNN (regions with convolutional neural networks) object detection algorithm. It provides the location of the vehicles in a box plot with detection scores.

Figure 5. A panoramic View of GoPro Max360

Figure 6. A View of GoPro Hero 9

Figure 7. An Illustration of Vehicle Detection

Camera-assisted visual data was explored in order to investigate potential sources of pollutant emission using video clips. For example, the peaks in On-Road BC on an intercity trip were extracted to attempt to identify the emission sources from prior traffic conditions such as speed, number and types of vehicles, roadway classification, and land-use in roadside environments. Figures 8, 9, and 10 show examples of this camera-assisted investigation.

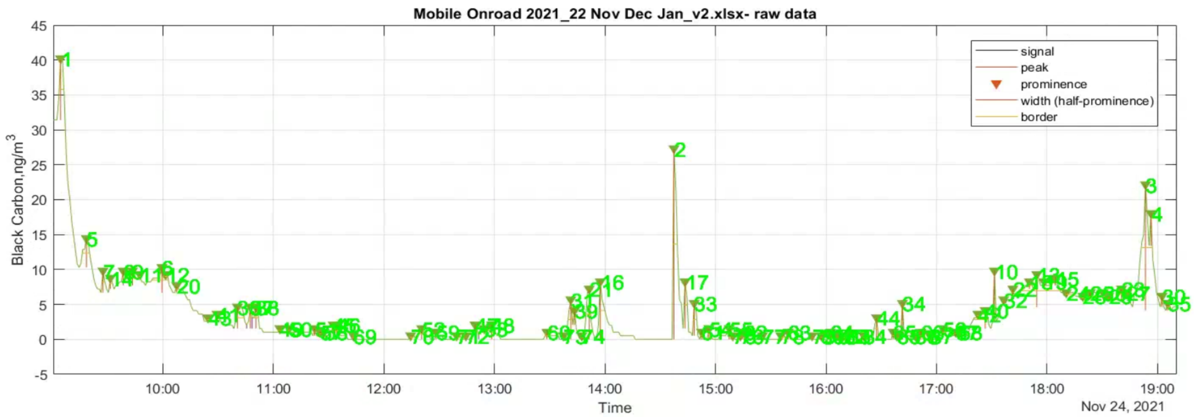

Figure 8. BC concentration measured On-Road During an Intercity Trip between Fresno and Berkeley on 11/23/2021

Note: The peaks were ranked by concentrations.

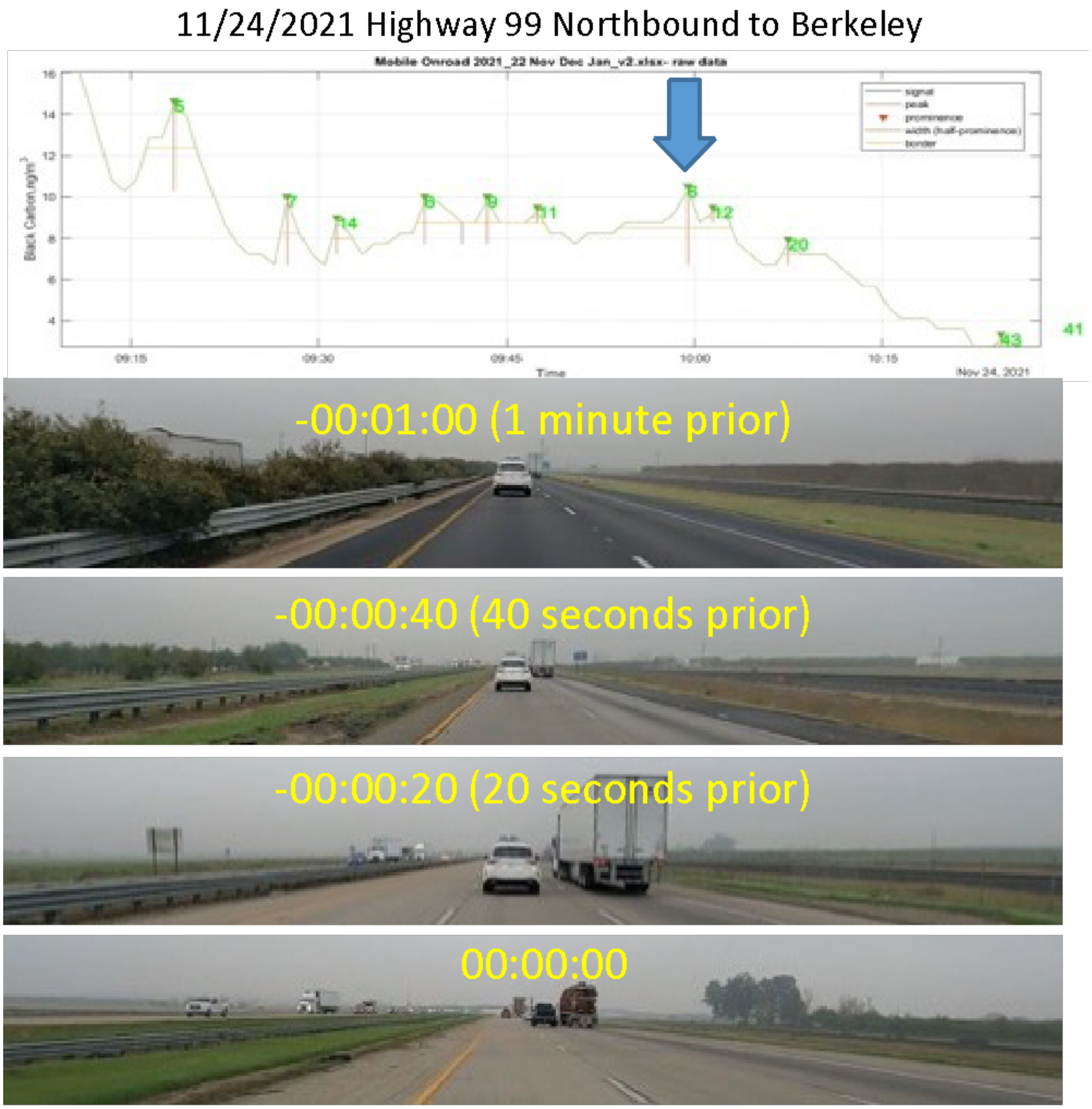

Figure 9. Example Peak 6 of BC Measured On-Road 11/24/2021 Highway 99 Northbound to Berkeley and the visual data extracted based on the times prior to the peak.

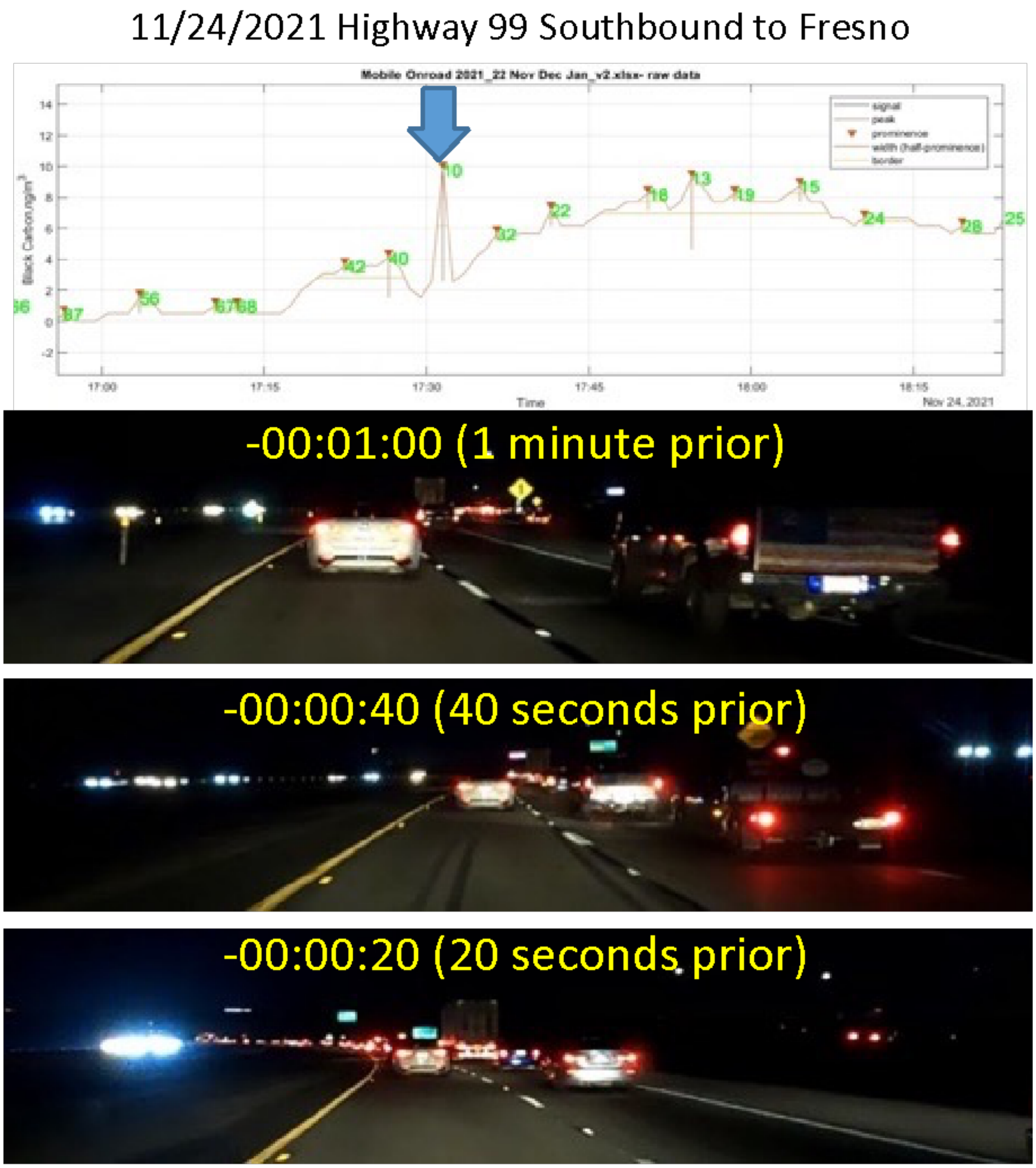

Figure 10. Example Peak 10 of BC Measured On-Road 11/24/2021 Highway 99 Southbound to Fresno and the visual data extracted based on the times prior to the peak

3.3 Air Quality on Bike Trails: Active Transportation Mode

Table 4 shows the summary statistics of the $PM_{2.5}$ and BC concentrations from bike trails and backyards. PM_{10} and PM_1 concentrations were nearly identical to $PM_{2.5}$ concentrations. On 8/31/2021, the concentration levels were higher than the following two days (9/17/2021 and 9/19/2021) because PM levels in the area were elevated by the wildfire smoke. On 9/23/2021, the levels became high again.

Table 4. Summary Statistics of $PM_{2.5}$ and BC Concentrations (Mg/M^3) on Bike Trails and in the Backyard

Sampling Date	Sample Type	Mean	Median	Range	StDev	Q1	Q3
8/31/2021*	BC Backyard	NA	NA	NA	NA	NA	NA
	BC Bike Trail	1.29	1.26	0.99	0.20	1.18	1.38
	$PM_{2.5}$ Backyard	40.46	40.94	7.47	1.75	39.14	41.46
	$PM_{2.5}$ Bike Trail	40.54	39.83	26.33	4.80	38.19	41.01
9/17/2021*	BC Backyard	NA	NA	NA	NA	NA	NA
	BC Bike Trail	0.74	0.66	2.24	0.36	0.53	0.82
	$PM_{2.5}$ Backyard	18.03	18.03	8.76	2.02	16.48	18.80
	$PM_{2.5}$ Bike Trail	18.17	16.88	33.30	5.05	15.30	19.35
9/19/2021	BC Backyard	0.13	0.12	0.38	0.06	0.08	0.15
	BC Bike Trail	0.23	0.15	1.39	0.24	0.08	0.28
	$PM_{2.5}$ Backyard	2.78	2.83	1.03	0.24	2.58	2.83
	$PM_{2.5}$ Bike Trail	3.38	2.93	7.20	1.36	2.48	3.60
9/23/2021*	BC Backyard	1.20	1.19	0.58	0.10	1.12	1.26
	BC Bike Trail	1.04	1.00	1.95	0.31	0.89	1.14
	$PM_{2.5}$ Backyard	41.02	42.49	13.13	4.04	37.34	44.29
	$PM_{2.5}$ Bike Trail	37.58	36.00	27.23	5.18	33.30	41.40
10/19/2021	BC Backyard	0.34	0.33	0.60	0.11	0.27	0.41
	BC Bike Trail	0.59	0.50	2.02	0.35	0.38	0.73
	$PM_{2.5}$ Backyard	10.38	10.30	1.55	0.27	10.30	10.56
	$PM_{2.5}$ Bike Trail	8.77	8.10	11.03	1.96	7.26	9.45

* Daily $PM_{2.5}$ levels were impacted by wildfire smokes in Fresno County.

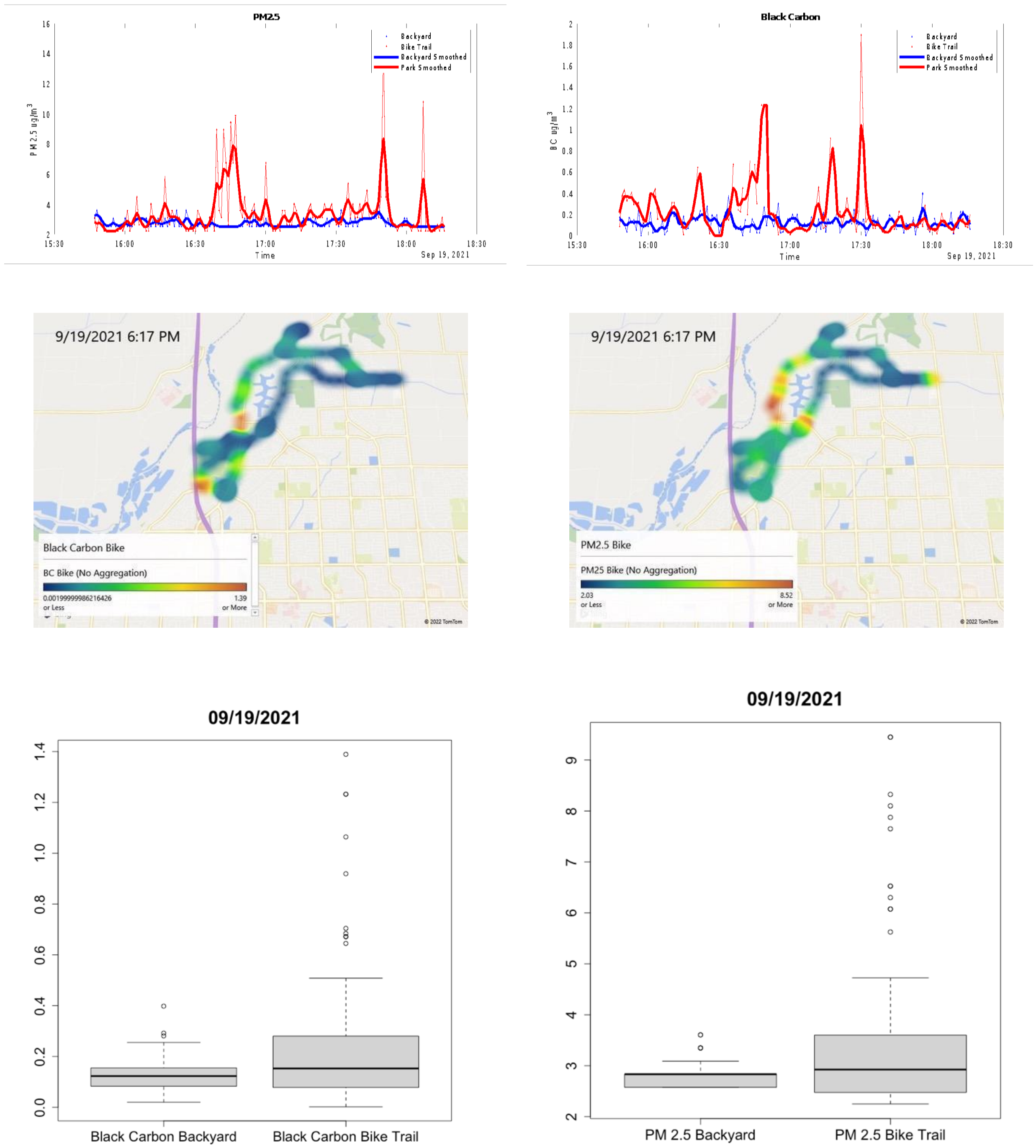

Figure 11. Time Series Plot, Concentration Heat Maps, and Box and Whisker Plots for BC and $PM_{2.5}$ Concentrations (μg/m^3) on Bike Trails, and in the Backyard on 9/19/21

In Figure 11, the time series plots show the minute-level BC and $PM_{2.5}$ data from the backyard and bike trail. It is evident that, in both data, bike trail data show more volatile behavior than that of the backyard for both datasets. Box and whiskers plots also indicate this result. The distribution is more skewed (to the right) in bike trail data than in backyard data. From the concentration heat maps, the overall air quality was very clean. The average $PM_{2.5}$ was 2.8 $\mu g/m^3$ in the backyard during this day, comparable to 3.1 $\mu g/m^3$ reported in the federal reference monitoring (FRM) station. It is notable that there was a small field fire across the riverbank from the park trails at around 16:45, when both BC and $PM_{2.5}$ concentrations increased concurrently, revealing warm colors on the heat maps.

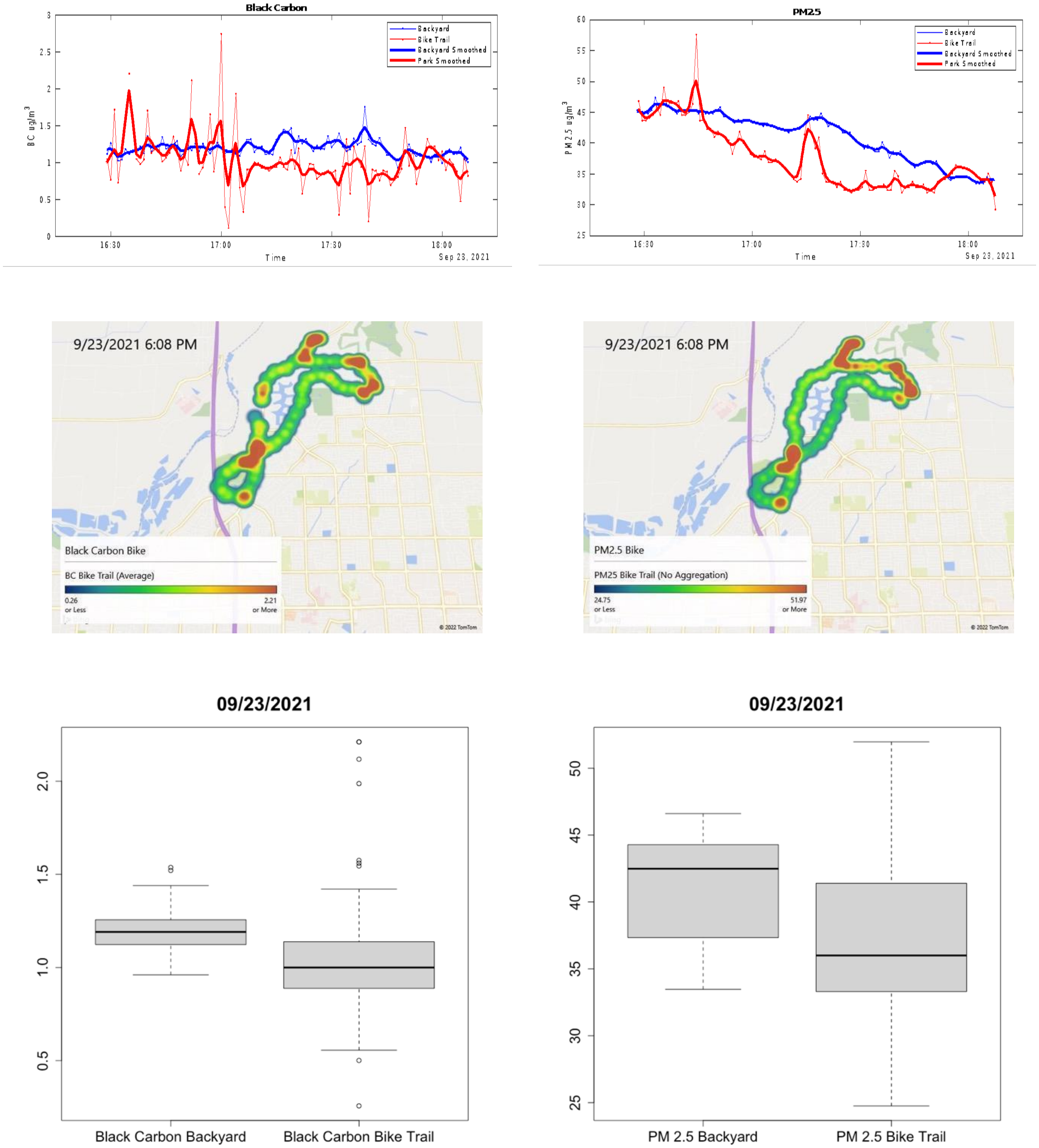

Figure 12. Time Series Plot, Concentration Heat Maps, and Box and Whisker Plots for BC and $PM_{2.5}$ Concentrations (μg/m^3) on Bike Trails, and in the Backyard on 9/23/21

In Figure 12, time series plots show the minute-level BC and $PM_{2.5}$ data from the backyard and bike trail. Unlike Figure 11, backyard data showed higher levels of concentration on 9/23/21, indicating the residential area is more polluted than the park area. However, the variability is higher in bike trail data than the backyard data. In both datasets, the distributions are fairly symmetric, except that there are a few outliers in the bike trail data for BC. The average $PM_{2.5}$ was 41.0 $\mu g/m^3$ in the backyard during this day, greater than the 30.1 $\mu g/m^3$ reported in the federal reference monitoring station during the same time period. This indicates that the local $PM_{2.5}$ concentration may be higher than that recorded at the FRM, and that the $PM_{2.5}$ concentration may be lower in the park trails. This may be because the $PM_{2.5}$ samplers in the backyard are closer to local traffic and the ground level, which is more prone to being directly impacted by local conditions.

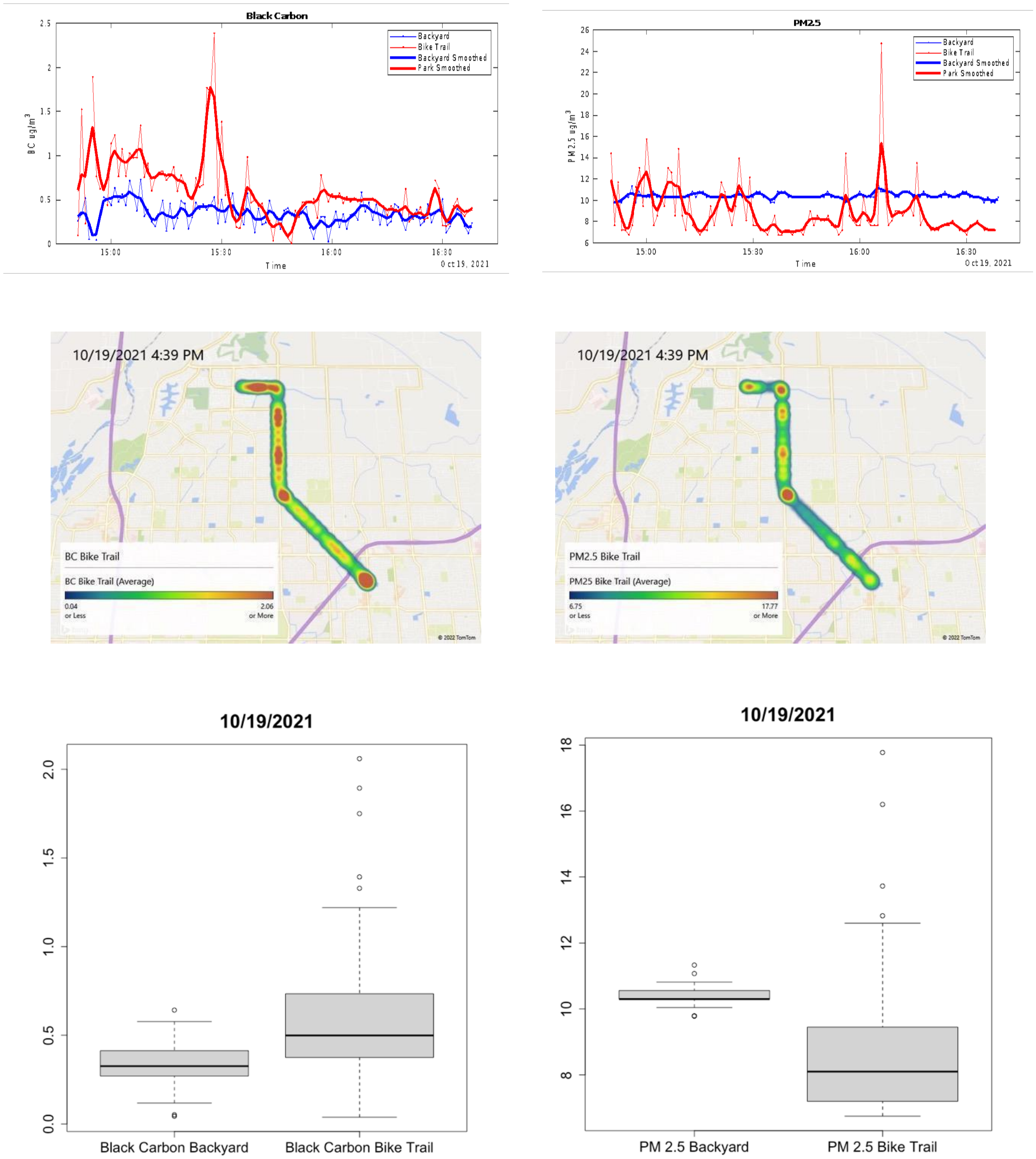

Figure 13. Time Series Plot, Concentration Heat Maps, and Box and Whisker Plots for BC and $PM_{2.5}$ Concentrations (μg/m³) on Bike trails and in the Backyard on 10/19/21

In Figure 13, median $PM_{2.5}$ level is higher for the backyard than the bike trails, while median BC is lower for the backyard. Since the route included more roadways compared to other sample days, the route's proximity to vehicle traffic contributed the elevated BC levels, especially right at the start where it passed by a high school after class. It is notable that the BC samples picked up the influence of traffic while the $PM_{2.5}$ data did not. The box and whiskers plots indicate that the bike trail data consistently had more variability than the backyard data.

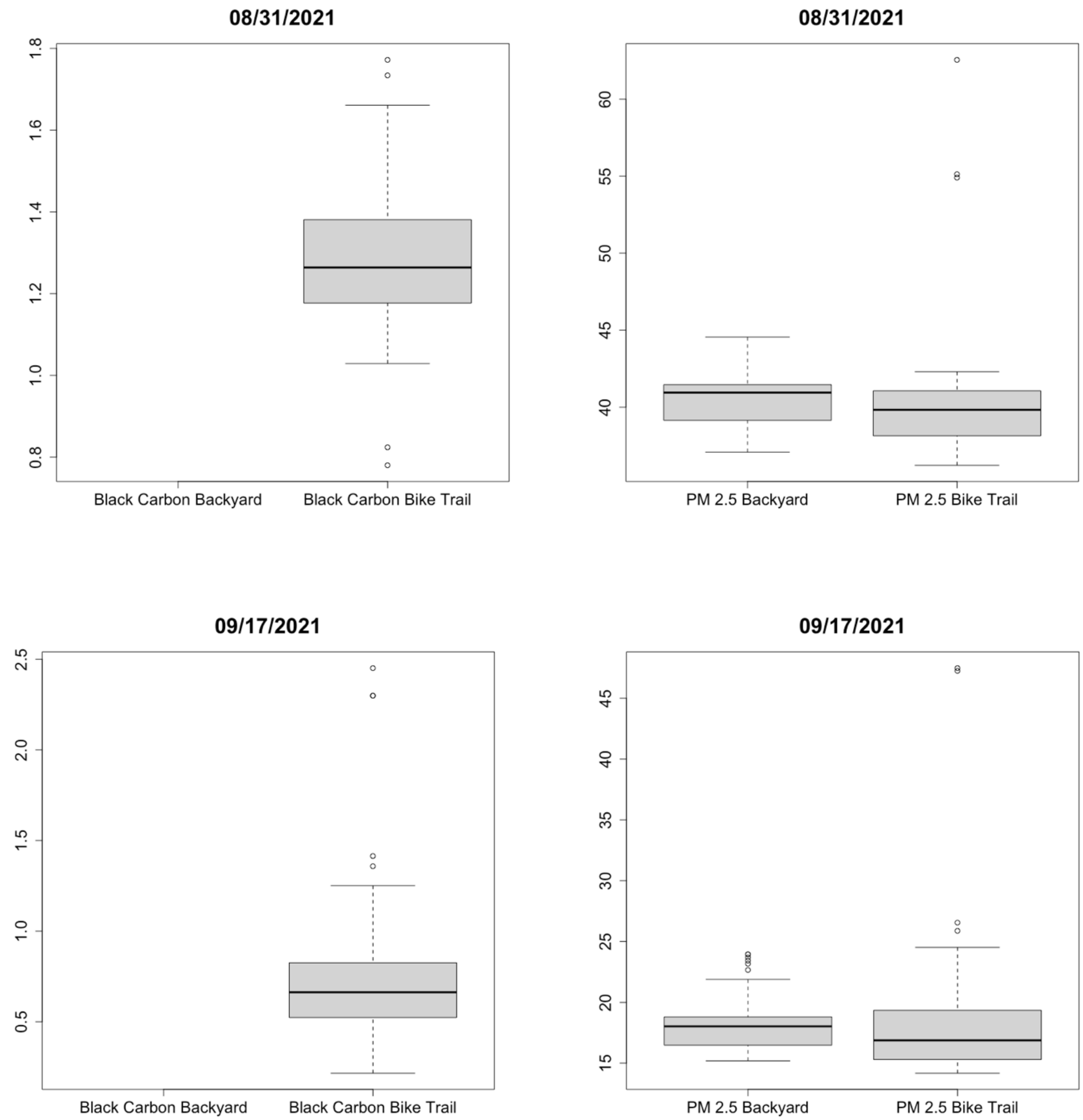

Figure 14. The Box and Whisker Plots for BC and $PM_{2.5}$ Concentrations (μg/m^3) on Bike Trails and in the Backyard on 8/31/21 and 9/17/21

BC data for the backyard is not available for these days, so no comparison can be made. The box plots show a somewhat similar distribution for $PM_{2.5}$. for both days. Overall, we can observe the following results from the bike trail samplings. The variability of $PM_{2.5}$ concentrations for bike trail data is greater than backyard data. The variability of BC concentrations for bike trail data is greater than that of backyard data. The following equations provide the actual numbers.

$$\{\text{Std Dev } (PM_{2.5\ Bike}) = 3.7\} > \{\text{Std Dev } (PM_{2.5\ Backyard}) = 1.7\}$$

$$\{\text{Std Dev } (BC_{Bike}) = 0.29\} > \{\text{Std Dev } (BC_{Backyard}) = 0.09\}$$

Next, we considered the mean of the ratio of $PM_{2.5}$ levels from the bike trail and $PM_{2.5}$ levels from the backyard, and the mean of the ratio of BC levels from the two locations. We observed that $PM_{2.5}$ concentration from the bike trail are almost identical to those from the backyard on average. However, BC concentrations from the bike trail are higher than those of the backyard. The following equations show the numerical results.

$$\text{Mean } [(PM_{2.5\ Bike})/(PM_{2.5\ Backyard})] = 0.997$$

$$\text{Mean } [(BC_{Bike})/(BC_{Backyard})] = 1.48$$

In addition, we calculated the mean of the ratio of $PM_{2.5}$ concentrations from the bike trail, and those reported by the FRM. BC is not monitored at FRM. The calculation shows that the bike trail has about a 21% higher concentration than FRM.

$$\text{Mean } [(PM_{2.5\ Bike})/(PM_{2.5\ FRM})] = 1.21$$

3.4 On-Road and In-Vehicle Air Quality in the Fresno Area

In-Vehicle and On-Road air monitoring was performed on Fresno Clovis roadways. There are six sampling routes. The acquisition dates are 4/3/2021, 4/4/2021,4/5/2021, 4/6/2021, 9/25/21, and 12/21/2021 respectively. PM_{10} and PM_1 concentrations were nearly identical to $PM_{2.5}$ concentrations.

Table 5. Summary Statistics of the On-Road and In-Vehicle $PM_{2.5}$ and BC Concentrations ($\mu g/m^3$) in the Fresno Area.

Sampling Date	Sample Type	Mean	Median	Range	StDev	Q1	Q3
4/3/2021	BC In-Vehicle	0.10	0.09	0.34	0.07	0.06	0.11
	BC On Road	10.90	0.71	133.76	25.10	0.37	4.69
	PM2.5 In-Vehicle	3.57	3.18	5.45	1.26	3.05	3.61
	PM2.5 On Road	7.42	6.90	8.14	1.66	6.26	7.99
4/4/2021	BC In-Vehicle	0.16	0.12	1.74	0.27	0.08	0.16
	BC On Road	0.93	0.89	1.50	0.40	0.63	1.21
	PM2.5 In-Vehicle	3.34	2.90	7.08	1.53	2.66	3.26
	PM2.5 On Road	9.44	9.33	3.64	0.74	8.86	9.85
4/5/2021	BC In-Vehicle	0.35	0.18	1.49	0.39	0.14	0.33
	BC On Road	48.14	3.23	860.72	146.62	1.01	9.48
	PM2.5 In-Vehicle	2.41	2.13	4.16	0.90	1.95	2.55
	PM2.5 On Road	6.23	5.68	6.30	1.55	5.27	6.39
4/6/2021	BC In-Vehicle	0.21	0.20	0.40	0.08	0.14	0.25
	BC On Road	1.08	0.74	3.52	0.84	0.45	1.56
	PM2.5 In-Vehicle	2.12	1.86	4.29	0.96	1.60	2.12
	PM2.5 On Road	6.03	5.65	8.93	1.55	5.01	6.48
9/25/2021	BC In-Vehicle	0.66	0.57	1.70	0.31	0.48	0.76
	BC On Road	30.92	8.97	266.33	55.25	3.15	32.28
	PM2.5 In-Vehicle	24.57	19.44	69.01	15.48	14.68	23.56
	PM2.5 On Road	70.91	66.94	220.05	28.18	58.44	75.94
12/21/2021	BC In-Vehicle	0.39	0.31	1.93	0.32	0.18	0.42
	BC On Road	34.07	16.80	194.16	41.98	2.49	52.77
	PM2.5 In-Vehicle	11.27	8.50	39.40	6.98	7.47	13.00
	PM2.5 On Road	47.46	47.70	18.90	3.66	45.68	49.95

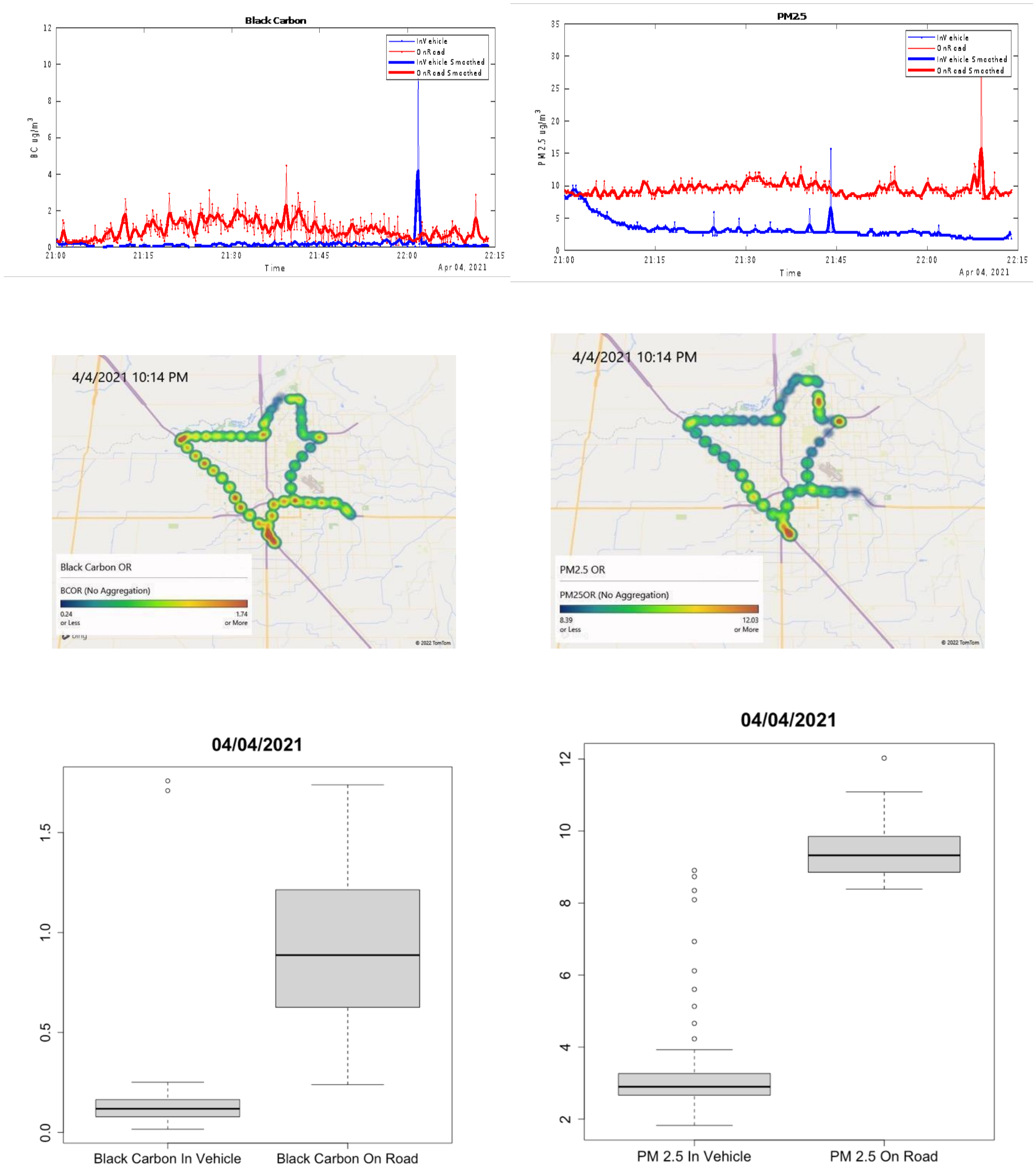

Figure 15. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations (μg/m^3) on 4/4/21

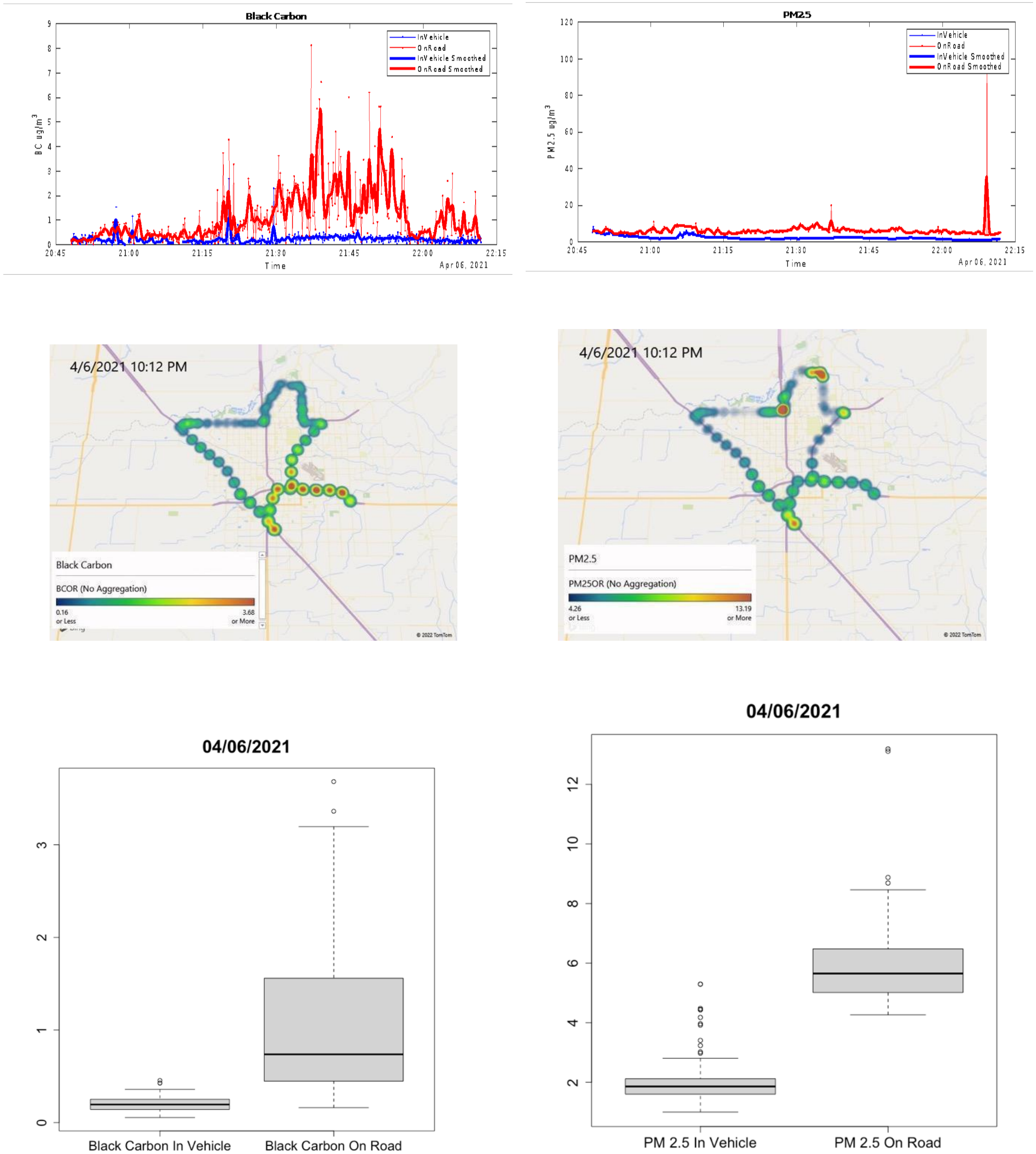

Figure 16. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations (μg/m^3) on 4/6/21

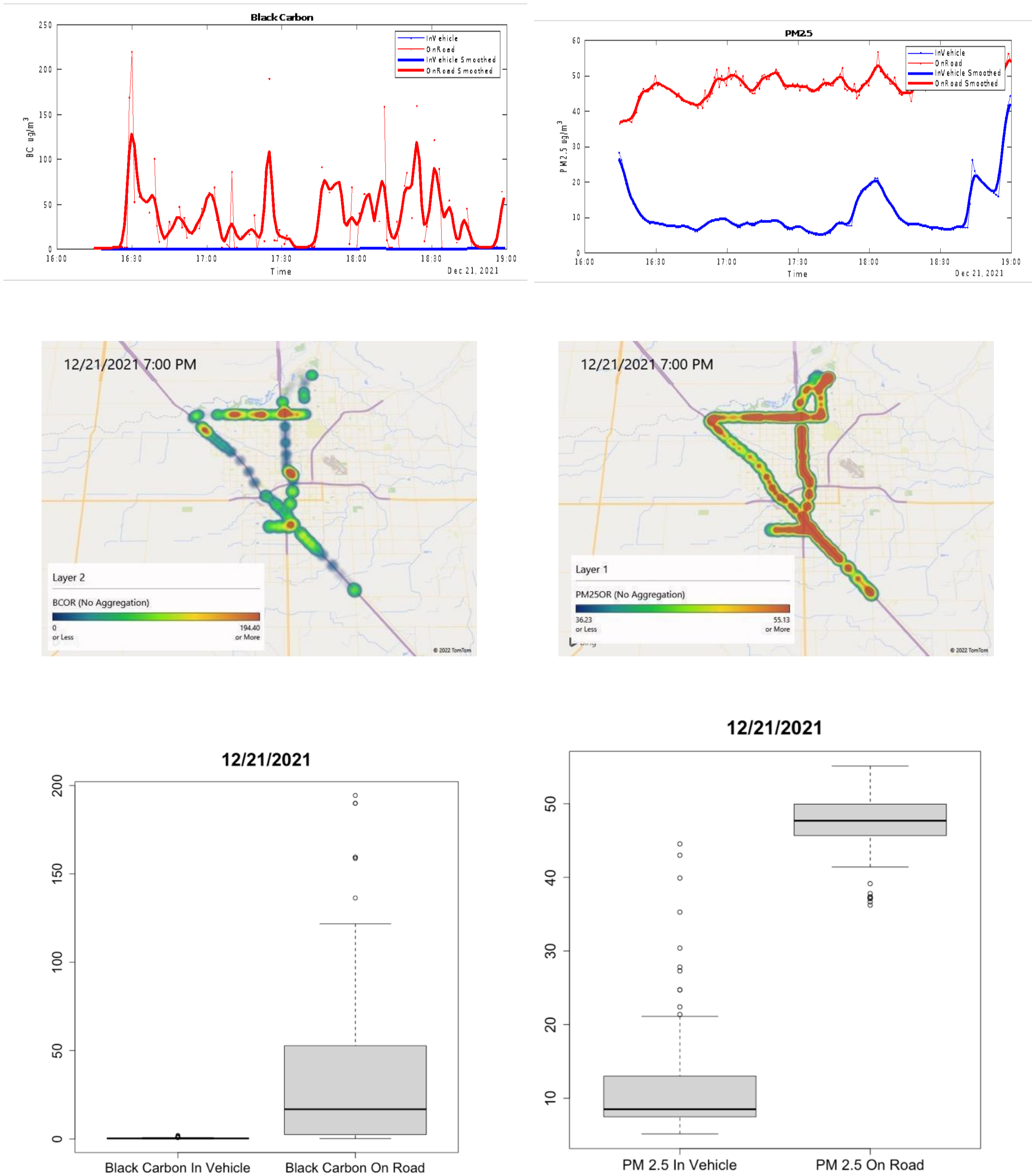

Figure 17. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations (μg/m³) on 12/21/21

In-Vehicle and On-Road parallel air sampling was performed to collect $PM_{2.5}$, BC, and PAHs on Highway 99 and Highway 41, Fresno on 12/21/2021 from 16:00 to 19:00. The Central Fresno $PM_{2.5}$ ranged from 27 to 34 $\mu g/m^3$ during the periods. The Air Quality Index ranged from level 2 (Yellow) to level 3 (Orange). On-Road $PM_{2.5}$ ranged from forty to fifty-five $\mu g/m^3$ during the sampling to fifty and sixty percent higher than regional $PM_{2.5}$. On-Road BC varied very frequently and was ten to one hundred times greater compared to In-Vehicle BC. The route and concentration heat map is shown below along with the time series of particle concentrations. As indicated by warm colors, higher $PM_{2.5}$ concentrations were observed near the Highway 41 and 99 connecting areas, where there was traffic congestion during rush hour, and the holiday shopping season was in full swing.

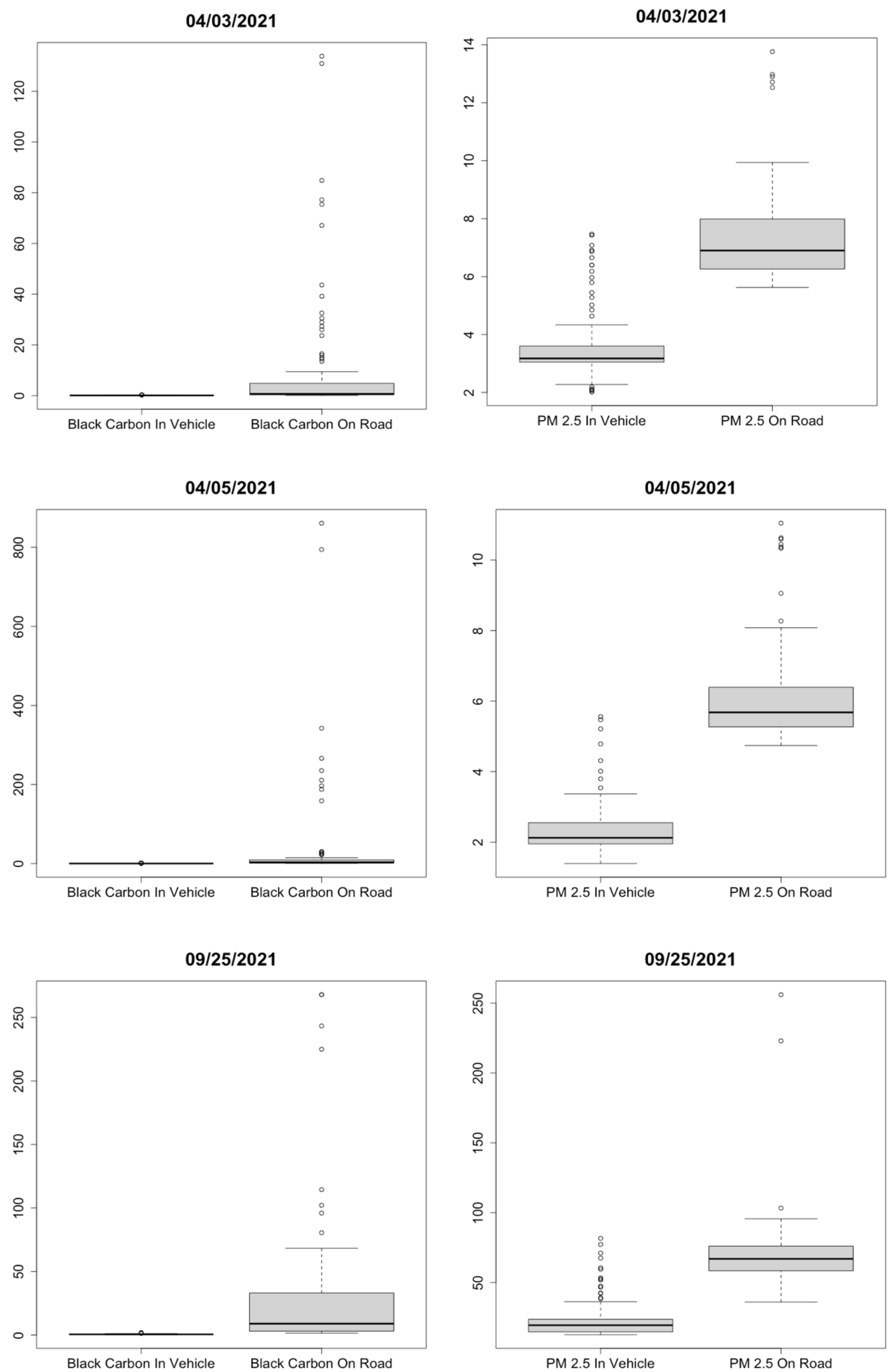

Figure 18. The Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) in the Fresno Area on 4/3/21, 4/5/21, and 9/25/21

Similar to the previous bike trail section, we have examined the overall variability and the mean of the ratios. The standard deviation of $PM_{2.5}$ concentrations from the On-Road monitors was greater than those of the In-Vehicle monitors. The standard deviation of BC concentrations greater On-Road than In-Vehicle. The numbers are shown below.

$$\{Std\ Dev\ (PM_{2.5\ On\text{-}Road}) = 6.2\} > \{Std\ Dev\ (PM_{2.5\ In\text{-}Vehicle}) = 4.5\}$$

$$\{Std\ Dev\ (BC_{\ On\text{-}Road}) = 45.0\} > \{Std\ Dev\ (BC_{\ In\text{-}Vehicle}) = 0.24\}$$

From the equations below, we can observe that, on average, On-Road $PM_{2.5}$ concentrations are almost three times higher than In-Vehicle concentrations, and On-Road BC concentrations are almost sixty-five times higher.

$$Mean\ [(PM_{2.5\ On\text{-}Road})/(PM_{2.5\ In\text{-}Vehicle})]_{Fresno} = 2.9$$

$$Mean\ [(BC_{\ On\text{-}Road})/(BC_{\ In\text{-}Vehicle})]_{Fresno} = 64.6$$

Lastly, it was calculated that, on average, On-Road $PM_{2.5}$ concentrations are twenty-one percent higher than those reported by the FRM. There is no BC data at the FRM to compare with.

$$Mean\ [(PM_{2.5\ On\text{-}Road})/(PM_{2.5\ FRM})] = 1.21$$

3.5 On-Road and In-Vehicle Air Quality During Intercity Trips

Intercity In-vehicle and On-Road air monitoring was performed. There are four round trips from Fresno to Berkeley (F-B-F) and one round trip from Fresno to Los Angeles (F-LA-F). The acquisition dates are 11/24/2021, 11/27/2021, 12/23/2021, 1/12/2022, and 12/26/2021 respectively. PM_{10} and PM_1 concentrations were nearly identical to $PM_{2.5}$ concentrations.

Table 6. Summary Statistics of the $PM_{2.5}$ and BC Concentrations ($\mu g/m^3$) of Inter-city Trips

Sampling Date	Sample Type	Mean	Median	Range	StDev	Q1	Q3
11/24/2021 (F-B-F Trip1)	BC In-Vehicle	0.24	0.19	0.98	0.18	0.11	0.31
	BC On Road	5.59	1.36	293.71	23.66	0.62	2.67
	PM2.5 In-Vehicle	2.75	1.03	24.46	3.51	0.26	5.41
	PM2.5 On Road	16.23	4.05	83.25	20.46	2.25	37.58
11/27/2021 (F-B-F Trip 2)	BC In-Vehicle	0.33	0.29	1.46	0.23	0.19	0.39
	BC On Road	3.11	1.68	202.69	13.03	1.28	2.24
	PM2.5 In-Vehicle	6.61	6.66	19.06	3.30	3.83	8.20
	PM2.5 On Road	25.00	26.46	46.58	10.73	16.78	33.88
12/23/2021 (F-B-F Trip3)	BC In-Vehicle	0.38	0.15	11.75	1.28	0.11	0.22
	BC On Road	25.50	0.65	701.86	87.05	0.32	1.93
	PM2.5 In-Vehicle	1.58	1.03	7.98	1.06	1.03	1.80
	PM2.5 On Road	5.93	4.73	51.08	4.49	3.60	6.75
12/26/2021 (F-LA-F)	BC In-Vehicle	0.21	0.13	4.68	0.30	0.08	0.24
	BC On Road	22.26	0.93	664.83	79.93	0.42	3.32
	PM2.5 In-Vehicle	2.17	1.55	13.65	1.84	1.03	2.83
	PM2.5 On Road	6.84	5.40	21.15	4.06	3.83	8.55
1/12/2022 (F-B-F Trip 4)	BC In-Vehicle	0.54	0.39	3.10	0.49	0.27	0.59
	BC On Road	55.21	1.77	850.09	114.81	1.36	25.76
	PM2.5 In-Vehicle	8.47	7.73	30.64	4.48	5.67	10.04
	PM2.5 On Road	41.35	40.39	60.53	11.72	35.78	48.60

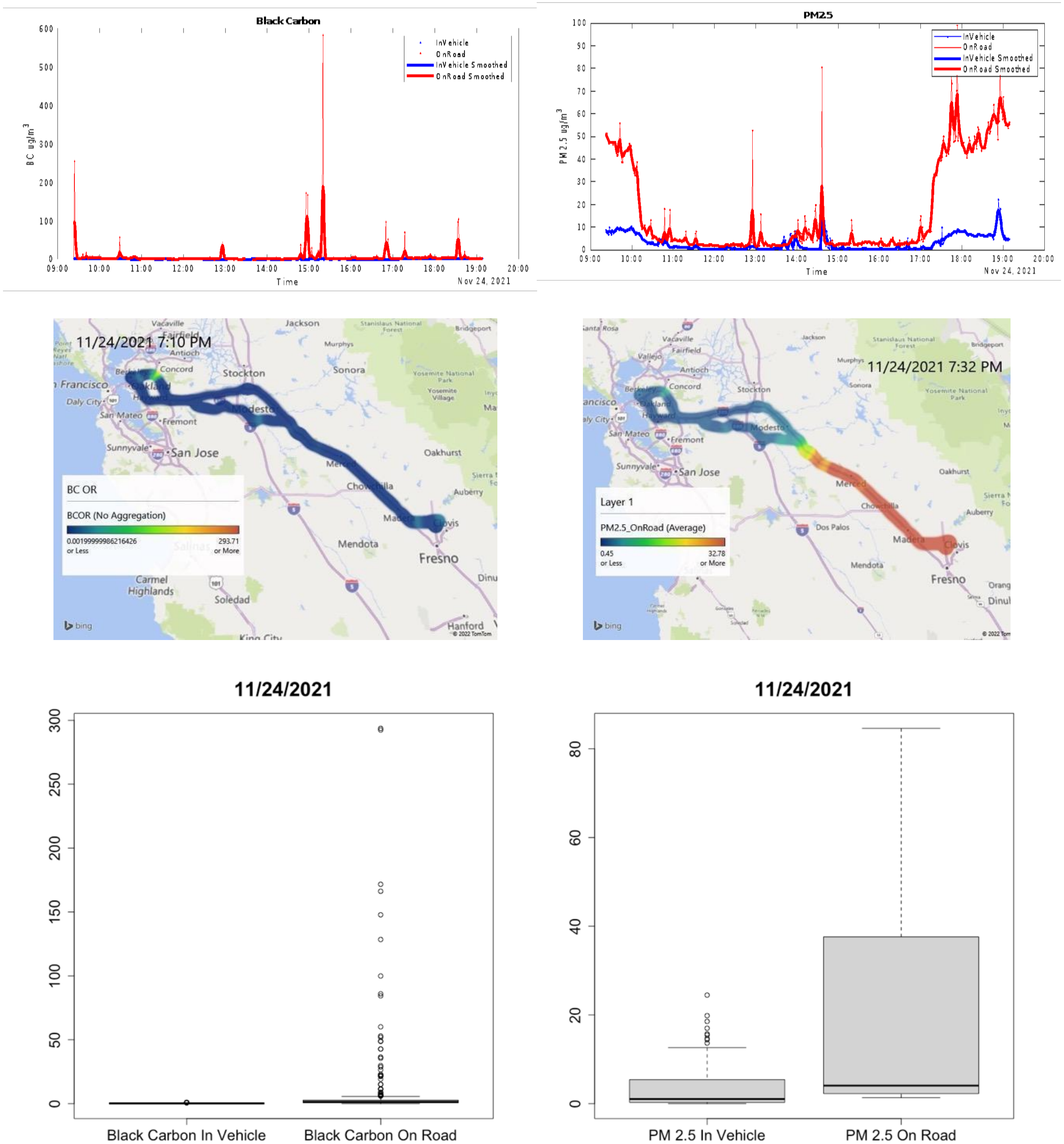

Figure 19. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations (µg/m^3) on 11/24/21 (F-B-F Trip 1)

The first trip between Fresno and Berkeley was on 11/24/21 (F-B-F Trip 1). The pollutant time series plots, concentration heat maps, and box and whisker plots for On-Road and In-Vehicle BC and $PM_{2.5}$ concentrations (μg/m^3) are illustrated in Figure 19.

The atmosphere was very stagnant and foggy in the morning. The average $PM_{2.5}$ concentration in the San Joaquin Valley at the FRM was 38 μg/m^3 during the corresponding morning and evening time periods. There was a high volume of Thanksgiving holiday traffic, and stop-and-go traffic jams throughout the trip. The On-Road $PM_{2.5}$ concentration in the San Joaquin Valley was seven to ten times higher than the concentration in the Bay area. In the Berkeley area, occasional spikes were related to traffic emissions, and dust blown from downtown construction, which did not last long. This illustrates the significant regional impacts of PM pollution in the San Joaquin Valley.

The average In-Vehicle $PM_{2.5}$ concentration (2.75 μg/m^3) during the trip was seventeen percent of the average concentration On-Road $PM_{2.5}$ (16.23 μg/m^3), indicating that the highly elevated On-Road pollution is reduced significantly when entering the vehicle cabin. The average In-Vehicle BC concentration (0.24 μg/m^3) during the trip was 4.3 percent of the average concentration On-Road BC (5.59 μg/m^3), indicating that the highly elevated On-Road BC is reduced even more significantly when entering the vehicle cabin compared to the reduction of $PM_{2.5}$ observed during the same trip on 11/24/2021. In-Vehicle concentrations were elevated when either a door or window was open. After the closure of doors, the concentration gradually decreased over time.

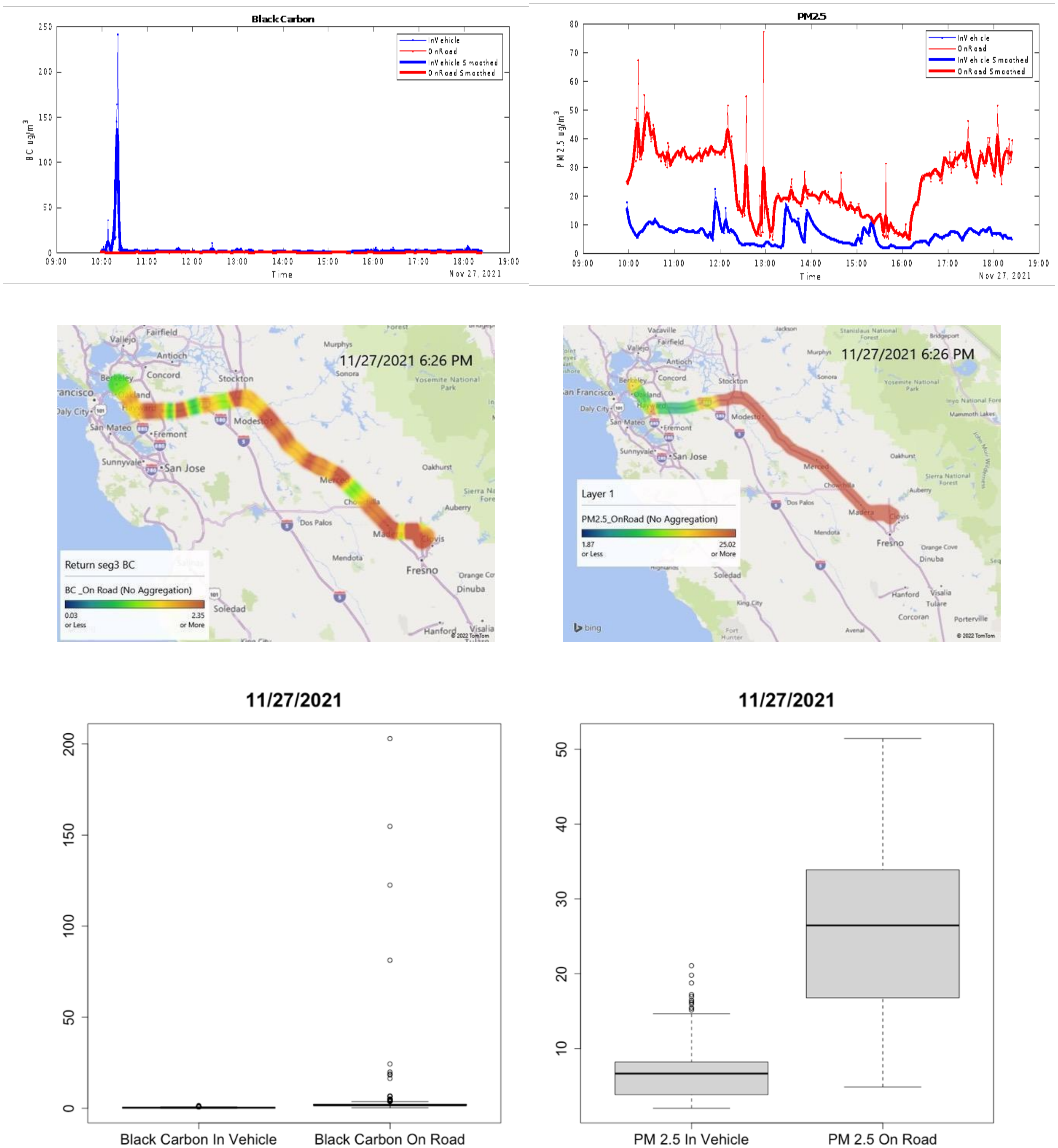

Figure 20. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations (μg/m³) on 11/27/21

The second trip between Fresno and Berkeley was on 11/27/21 (F-B-F Trip 2). The pollutant time series plots, concentration heat maps of On-Road samples, and box and whisker plots for On-Road and In-Vehicle BC and $PM_{2.5}$ concentrations (μg/m^3) are given in Figure 20. A high volume of motorcycles and trucks at the outset must have contributed the elevated concentrations of BC and $PM_{2.5}$. The duration at the Berkeley area was from 12:36 to 16:08. At 16:40 motorcycles and trains were observed, but they did not leave a significant signal.

The average $PM_{2.5}$ concentration in the San Joaquin Valley at the FRM was 25.6 μg/m^3 during the corresponding time periods. The time series and the heat map show high On-Road $PM_{2.5}$ concentration in the San Joaquin Valley in the morning (35 μg/m^3) and evening (31 μg/m^3), compared to the average $PM_{2.5}$ concentration in the Bay area (16 μg/m^3). Compared to the 11/24/21 sample, the average concentration difference between the two areas was smaller on 11/27/21. The On-Road $PM_{2.5}$ concentration in the San Joaquin Valley was about two times higher than the concentration in the Bay area. Still, the data illustrates the significant regional impacts of PM pollution in the San Joaquin Valley.

The average In-Vehicle $PM_{2.5}$ concentration (6.6 μg/m^3) during the trip was twenty-six percent of the average concentration of On-Road $PM_{2.5}$ (25.6 μg/m^3), indicating that the highly elevated On-Road pollution is reduced significantly when entering the vehicle cabin. The average In-Vehicle BC concentration (0.33 μg/m^3) during the trip was ten and a half percent of the average concentration of the On-Road BC (3.1 μg/m^3), indicating that the highly elevated On-Road BC is reduced even more significantly when entering the vehicle cabin compared to the reduction of $PM_{2.5}$. In-Vehicle concentrations were elevated when either a door or window was open. After the closure of doors, the concentrations gradually decreased over time.

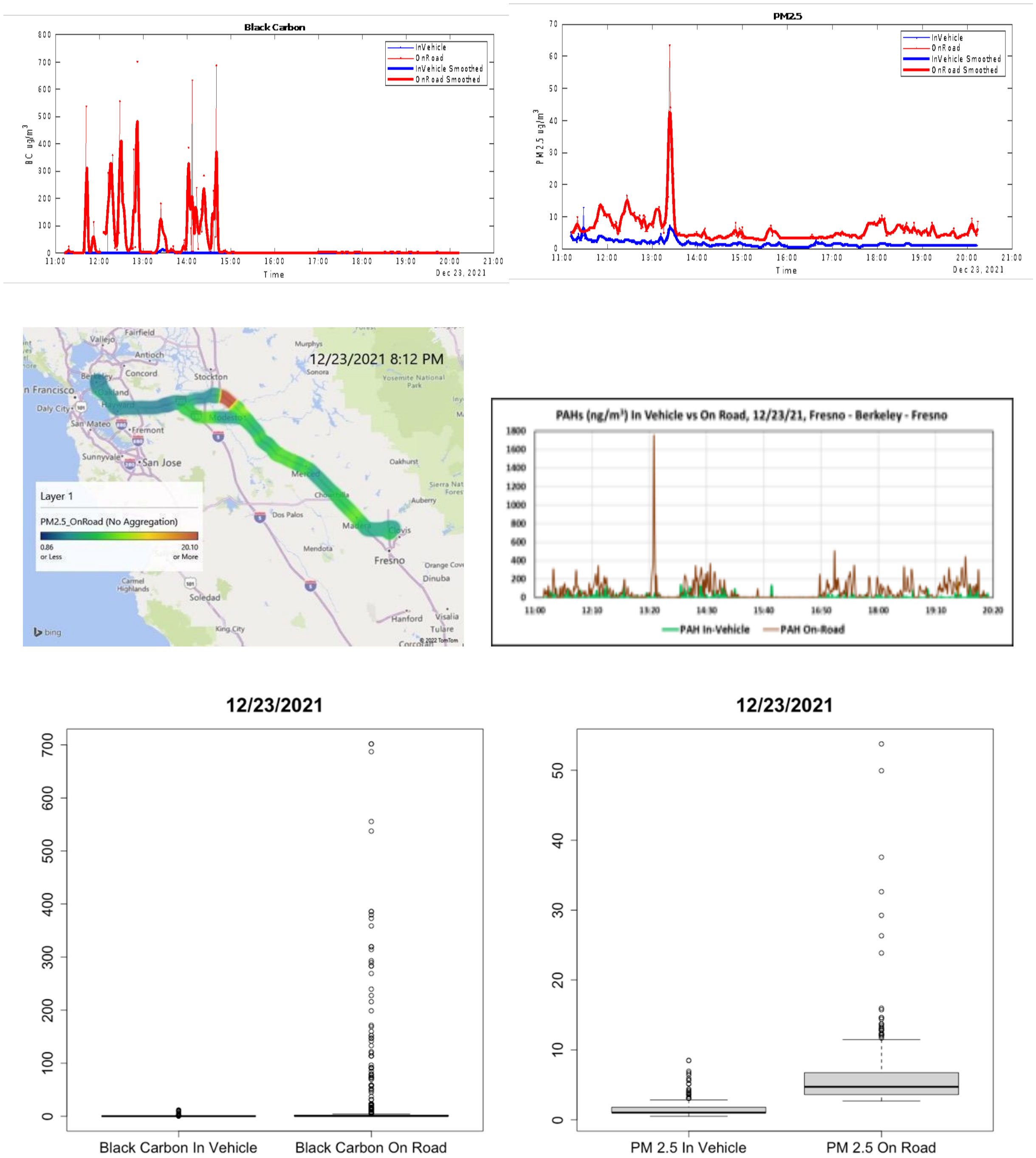

Figure 21. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations ($\mu g/m^3$) during the Fresno to Berkeley Trip on 12/23/21

The third trip between Fresno and Berkeley was on 12/23/21 (F-B-F Trip 3). The pollutant time series plots, concentration heat maps of On-Road samples, and box and whisker plots for BC and $PM_{2.5}$ concentrations ($\mu g/m^3$) On-Road and In-Vehicle are illustrated in Figure 21.

It rained in the morning and cleared up around 12:00. Air quality was very good. The average $PM_{2.5}$ in the San Joaquin Valley at the FRM was 2.3 $\mu g/m^3$ during the matching time periods. The difference between the On-Road $PM_{2.5}$ concentration in the San Joaquin Valley in the morning (8.3 $\mu g/m^3$) and evening (5.8 $\mu g/m^3$), and the average $PM_{2.5}$ concentration in the Bay area (3.8 $\mu g/m^3$) was the smallest compared to the previous trips on 11/24/21 and 11/27/21. The On-Road $PM_{2.5}$ concentration in the San Joaquin Valley was still maintained at about 1.5 to 2.2 times higher than the concentration in the Bay area, even when the air quality in the San Joaquin Valley was very good.

The average In-Vehicle $PM_{2.5}$ concentration (1.6 $\mu g/m^3$) during the trip was twenty-seven percent of the average concentration of the On-Road $PM_{2.5}$ (5.9 $\mu g/m^3$), indicating that the highly elevated On-Road pollution is reduced significantly when entering the vehicle cabin. The average In-Vehicle BC concentration (0.38 $\mu g/m^3$) during the trip was 1.5 percent of the average concentration of the On-Road BC (25.5 $\mu g/m^3$), indicating that the highly elevated On-Road BC concentration is reduced even more significantly when entering the vehicle cabin compared to the reduction of $PM_{2.5}$. Although the overall air quality was good, a heavy-duty diesel truck emitted a visible amount of smoke in front of the sampling vehicle for several minutes at 13:22 on Highway 99. This On-Road source can explain the high amount of emissions that were synchronously observed in PM_{10}, $PM_{2.5}$, PM_1, BC, and PAHs in both the On-Road and In-Vehicle aerosol monitors.

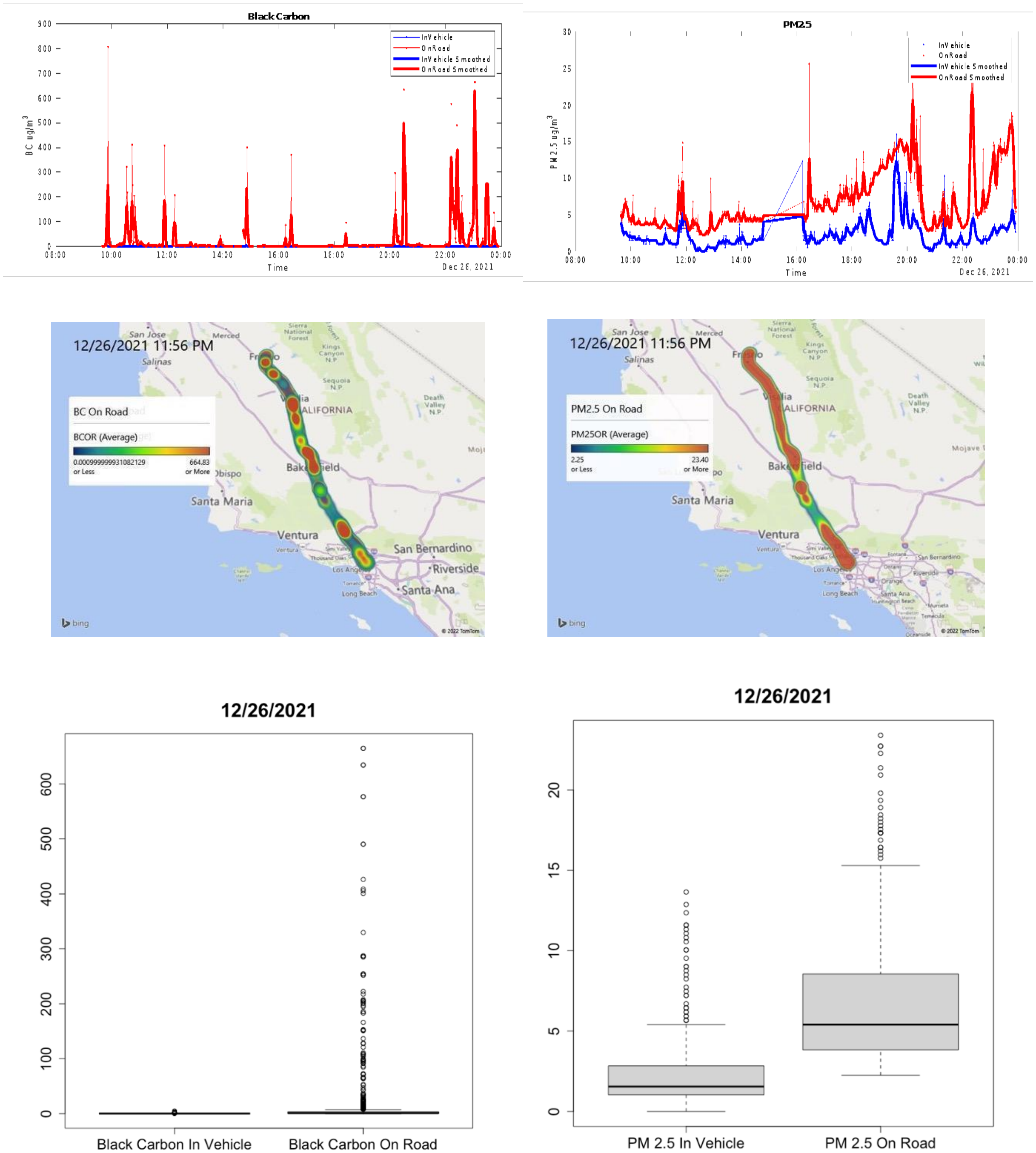

Figure 22. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations (μg/m^3) during the Fresno-Los Angeles Trip on 12/26/21

This was the only trip between Fresno and Los Angeles on 12/26/21 (F-LA-F Trip). The pollutant time series plots, concentration heat maps of On-Road samples, and box and whisker plots for BC and $PM_{2.5}$ concentrations (μg/m^3) On-Road and In-Vehicle are illustrated in Figure 22.

It was a clear and sunny day with good air quality. The average $PM_{2.5}$ in the San Joaquin Valley at FRM was 10.5 μg/m^3 during the matching time periods. Unlike the $PM_{2.5}$ concentrations observed from the Fresno-Berkeley trips, the difference between the On-Road $PM_{2.5}$ concentration in the San Joaquin Valley in the morning (4.2 μg/m^3) and evening (9.5 μg/m^3), and the average $PM_{2.5}$ concentration in the Los Angeles area (7.7 μg/m^3) was comparable and lower than that reported by the FRM, although it was observed from only one trip. The $PM_{2.5}$ concentrations were lower in the morning and then increased at night, throughout the San Joaquin Valley south of Fresno.

There was a significant difference between the On-Road BC concentration in the San Joaquin Valley in the morning (32 μg/m^3) and evening (64 μg/m^3), and the average BC concentration in the Los Angeles area (5.2 μg/m^3). The On-Road BC concentration in the San Joaquin Valley was about six to twelve times higher than the concentration in the Los Angeles area, even when the air quality in each area was relatively good. The average In-Vehicle $PM_{2.5}$ concentration (2.2 μg/m^3) during the trip was thirty-two percent of the average concentration of the On-Road $PM_{2.5}$ concentration (6.8 μg/m^3). On-Road pollution is reduced by at least two thirds when entering the vehicle cabin when air quality was relatively clear. The average In-Vehicle BC concentration (0.21 μg/m^3) during the trip was 0.9 percent of the average concentration of the On-Road BC (22.3 μg/m^3), indicating that the highly elevated On-Road BC is reduced even more significantly when entering the vehicle cabin compared to the reduction of $PM_{2.5}$ as observed from other intercity trips in this study.

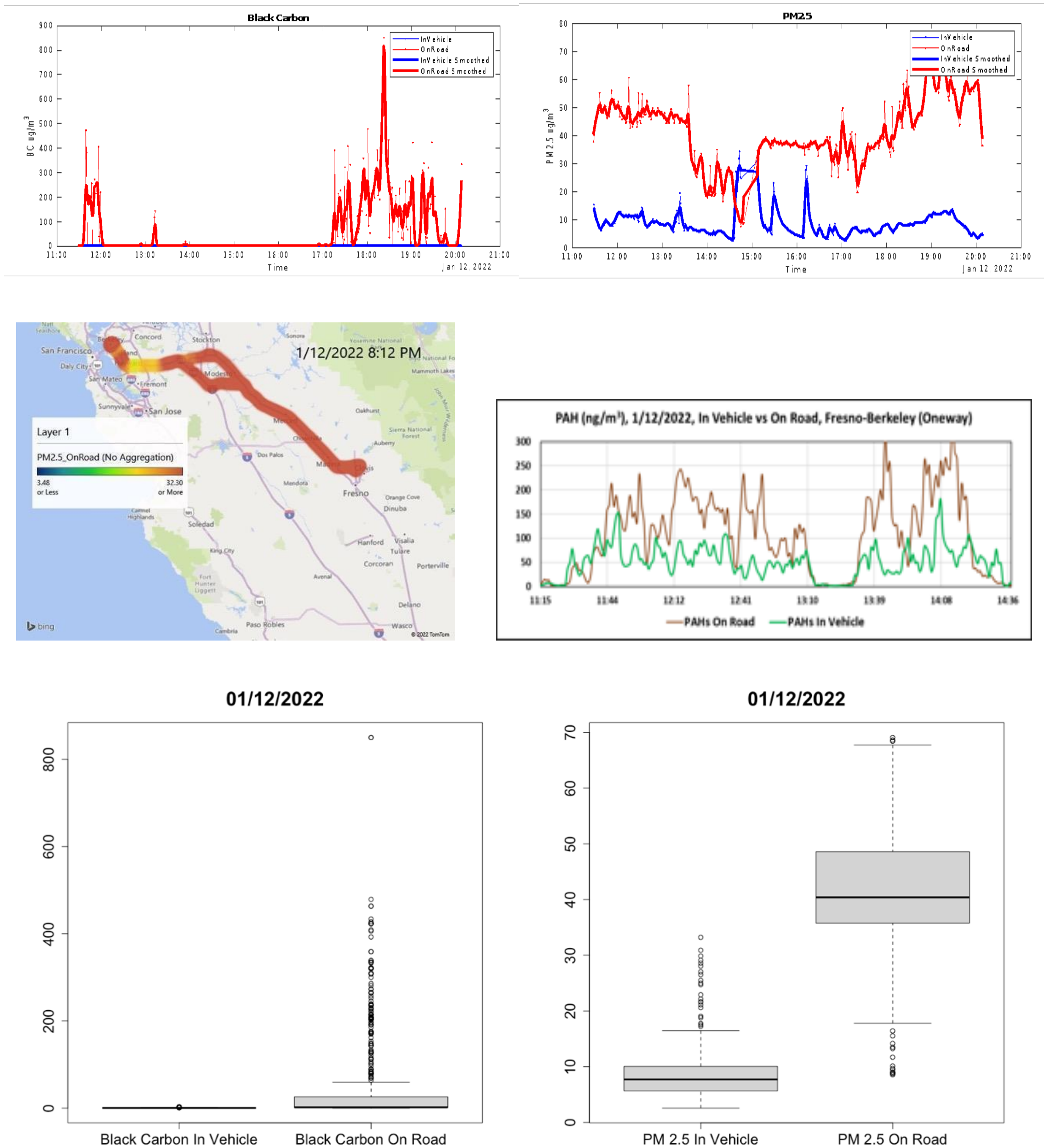

Figure 23. Time Series Plots, Concentration Heat Maps, and Box and Whisker Plots for On-Road and In-Vehicle BC and $PM_{2.5}$ Concentrations (μg/m³) during the Fresno-Berkeley Trip on 1/12/22

The fourth trip between Fresno and Berkeley was on 1/12/22 (F-B-F Trip 4). The pollutant time series plots, concentration heat maps of On-Road samples, and box and whisker plots for BC and $PM_{2.5}$ concentrations ($\mu g/m^3$) On-Road and In-Vehicle are illustrated in Figure 23. The $PM_{2.5}$ concentrations were very high (above 45 $\mu g/m^3$) throughout the San Joaquin Valley at Manteca, Modesto, Turlock, and Merced. Higher BC was also observed in the Valley at night.

The average $PM_{2.5}$ concentration in the San Joaquin Valley at the FRM was 30.7 $\mu g/m^3$ during the matching time periods. The time series and the heat map show that even the average $PM_{2.5}$ concentration in the Bay area (32 $\mu g/m^3$) was comparable to high On-Road $PM_{2.5}$ concentration in the San Joaquin Valley in the morning (46 $\mu g/m^3$) and evening (52 $\mu g/m^3$).

Compared to the previous F-B-F trip samples, the average concentration difference between the two areas was the smallest on 1/12/22, mainly because of very high $PM_{2.5}$ levels in the Bay area. The On-Road $PM_{2.5}$ concentration in the San Joaquin Valley was 1.4 to 1.6 times higher than the concentration in the Bay area. This data illustrates the significant regional impact of PM pollution both in the Bay area, and the San Joaquin Valley.

The average In-Vehicle $PM_{2.5}$ concentration (8.5 $\mu g/m^3$) during the trip was twenty percent of the average concentration of the On-Road $PM_{2.5}$ (41.4 $\mu g/m^3$), indicating the significant reduction of PM entering the vehicle cabin. The average In-Vehicle BC concentration (0.54 $\mu g/m^3$) during the trip was 0.98 percent of the average concentration of the On-Road BC (55.2 $\mu g/m^3$), indicating that the highly elevated On-Road BC level is reduced even more significantly when entering the vehicle cabin compared to the reduction of $PM_{2.5}$. It was consistently observed that the In-Vehicle concentrations were elevated when either a door or window was open. After the closure of doors, the concentrations gradually decreased over time. Exposure to transportation particulate matter increased with the opening of windows, doors, and the rear door when passengers got out of the car and loading or unloading the things. During the F-B-F Trip 4 (1/12/22), there was an instance where the In-Vehicle $PM_{2.5}$ concentration became higher than the On-Road $PM_{2.5}$. This was because the engine was kept running while the rear door was open for unloading, so the In-Vehicle particle monitors in the back directly detected a high level of particles.

The overall results from the five intercity trips indicate the following: the standard deviations were higher for On-Road rather than In-Vehicle $PM_{2.5}$ and BC concentrations .

$\{\text{Std Dev } (PM_{2.5\ \text{On-Road}}) = 10.3\} > \{\text{Std Dev } (PM_{2.5\ \text{In-Vehicle}}) = 2.8\}$

$\{\text{Std Dev } (BC_{\text{On-Road}}) = 63.7\} > \{\text{Std Dev } (BC_{\text{In-Vehicle}}) = 0.5\}$

The means of the ratios of $PM_{2.5}$ and BC concentration from On-Road and In-Vehicle monitors were calculated. These showed that the concentrations of On-Road $PM_{2.5}$ are almost four times higher than the In-Vehicle concentrations, and BC concentrations are sixty-two times higher than the respective In-Vehicle concentrations.

$$\text{Mean } [(PM_{2.5 \text{ On-Road}})/(PM_{2.5 \text{ In-Vehicle}})]_{\text{Intercity}} = 4.3$$

$$\text{Mean } [(BC_{\text{ On-Road}})/(BC_{\text{ In-Vehicle}})]_{\text{Intercity}} = 61.8$$

In other words, the average In-Vehicle/On-Road ratios were twenty-four percent and 3.6 percent for $PM_{2.5}$ and BC concentrations respectively, which illustrates that seventy-six and ninety-six percent of On-Road PM and BC pollutants, respectively, are removed when entering the vehicle cabin.

$$\text{Mean } [(PM_{2.5 \text{ In-Vehicle}})/(PM_{2.5 \text{ On-Road}})]_{\text{Intercity}} = 0.24$$

$$\text{Mean } [(BC_{\text{ In-Vehicle}})/(BC_{\text{ On-Road}})]_{\text{Intercity}} = 0.036$$

In addition, $PM_{2.5}$ concentration is twenty-one percent higher than that of the FRM, on average. Data on BC concentrations was not obtained from the FRM.

$$\text{Mean } [(PM_{2.5 \text{ On-Road}})/(PM_{2.5 \text{ FRM}})] = 1.21$$

4. Summary & Conclusions

In this study, we established the characterization methodology for inhalable exposure to transportation-emitted particulate matter including PM_{10}, $PM_{2.5}$, PM_1, BC, and PAHs. These particulate pollutants were measured concurrently in different transit modes and microenvironments, including bike trails, On-Road, In-Vehicle, local, and intercity environments to understand the contribution of immediate roadway emissions to personal exposure. The geographical information system incorporated pollution data on the map to enable spatio-temporal data analysis. The camera-assisted visual data of the surrounding environment during the transit air sampling was used for the identification of potential sources of pollutants. The utilization of cameras (GoPro Max 360 and GoPro Hero9) allowed us to examine potential emission sources and their association with factors such as traffic conditions, speed, number of vehicles, roadway types, land cover, and other secondary data. Roadway types and traffic conditions had an impact on On-Road $PM_{2.5}$. We will continue this analysis in StarTraq III.

In this study, we were able to conclude the following:

1. Relationships between PM species: PM_{10} and PM_1 concentrations were nearly identical to $PM_{2.5}$ concentrations in every microenvironment. The correlation with BC and $PM_{2.5}$ in On-Road samples became obvious as soon as we began collecting data. Spatio-temporal analysis on the relationships will be continued.

2. Variability of particle concentrations: The variability of particle concentrations was greater in the bike trail and On-Road samples than for the backyard or In-Vehicle samples. This is explained by the fact that the aerosol monitors were moving while collecting bike trail or On-Road samples, and were stationary inside the vehicle and in the backyard.

3. Bike trail vs. backyard: Bike trail PM concentrations were nearly identical (99.7 percent) to the ambient PM concentrations measured at the backyard. The average BC concentration level was forty-eight percent higher from the bike trail sample than from the backyard, implying that immediate contact with BC emissions on the roadways.

4. Reduction of In-Vehicle $PM_{2.5}$ and BC: In-Vehicle particle concentrations were significantly reduced to a safe level compared to the On-Road concentrations. In-Vehicle $PM_{2.5}$ was thirty-one percent of On-Road $PM_{2.5}$, while In-Vehicle BC was 5.5 percent of On-Road BC when local and intercity data were combined. In-Vehicle concentrations were elevated when either a door or window was open, allowing On-Road pollution to enter the vehicle. In-Vehicle concentrations were elevated significantly when doors were opened while the engine was running. After closing the doors, concentrations gradually decreased over time.

5. Intense On-Road concentrations during intercity and local sampling: On-Road $PM_{2.5}$ concentrations were 2.9 times higher than In-Vehicle concentrations in the Fresno roadway sampling. On-Road $PM_{2.5}$ concentrations were 4.3 times higher than the corresponding In-Vehicle concentrations on the intercity trips. On-Road BC concentrations were sixty-five times higher than In-Vehicle BC concentrations in the Fresno roadway sampling. On-Road BC concentrations were sixty-two times higher than In-Vehicle BC concentrations on intercity trips.

6. San Joaquin Valley and Bay Area: The PM concentrations measured On-Road on trips to the Bay Area demonstrated that the San Joaquin Valley has increased ambient $PM_{2.5}$ and BC compared to the Bay Area, on every trip, regardless of the daily change to air quality.

7. $PM_{2.5}$ concentrations were consistently measured twenty-one percent higher than those of the FRM, on average, for all types of samples. BC data was not obtained from the FRM. The air sampling inlet of the monitors was closer to the ground level and near the emission sources compared to the FRM and portable aerosol monitors do not control moisture. These two factors may have contributed to the increased levels of portable aerosol monitoring data.

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