Indoor and outdoor air quality at Harriet Tubman Middle School and the design of mitigation measures: Phase II & III report

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1 Executive summary

On January 8th, 2018, Portland Public Schools selected Portland State University to conduct monitoring and modeling to assess indoor and outdoor air quality and air flow conditions at Harriet Tubman Middle School (HTMS) in Portland, OR. Portland State University completed Phase I (from February 1, 2018 to April 19, 2018), of the proposed project and released a report to Portland Public Schools on April 18, 2018. Portland State University has now completed Phase II (from August 20, 2018 to October 19, 2018) and Phase III (from April 18, 2019 to June 18, 2019) monitoring which included the following four objectives:

Objective 1: Measure exposure concentrations of air pollutants of concern (traffic-related air pollutants as well as some criteria air pollutants) inside HTMS.

Objective 2: Measure exposure concentrations and spatial variability of air pollutants of concern in the near-vicinity of HTMS.

Objective 3: Test the efficiency of the newly installed heating, ventilation and air-conditioning (HVAC) system to remove traffic-related air pollutants from building supply air, initially and after one school year.

Objective 4: Evaluate the potential for infiltration of traffic-related air pollution across the building envelope.

This report serves to summarize the findings of the Phase II and III efforts, including: measurements of indoor and outdoor levels of air pollution, quantification of the efficiency of the HVAC system and building renovation to reduce indoor levels of traffic-related air pollution, and recommendations for maintaining installed air treatment systems.

1.1 Key findings:

- Consistent with Phase I monitoring results, Phase II and Phase III monitoring continue to demonstrate that HTMS school grounds are impacted by air pollution from Interstate 5.
- Outdoor levels of traffic-related air pollution are elevated near the freeway, and, depending on meteorology and time, are elevated above neighborhood backgrounds levels.
- PSU-recommended air cleaning systems in the renovated heating, ventilation, and air-conditioning system have generally high removal efficiencies for both gas and particle-phase air pollution of concern (see Table E1 and E2).
    - Removal efficiencies of some gas-phase compounds (notably, NO_2 and styrene) have decreased from September 2018 – June 2019 (Table E1).

Table E1. Calculated removal efficiencies of gas-phase air pollutants.

Compound	Advertised removal*	Sept. 2018	Oct. 2018	Jan. 2019	Feb. 2019	Mar. 2019	Apr. 2019	Jun. 2019	Calculated uncertainty**
NO_2	98%	N.A.	96%	92%	99%	>99%	N.A.	61%	
styrene	>99%	92%	95%	42%	71%	95%	63%	50%	65%
1,3,5-trimethylbenzene	>99%	84%	93%	60%	72%	100%	100%	94%	29%
1,2,4-trimethylbenzene	>99%	96%	93%	84%	83%	100%	99%	92%	9%
o-xylene	>99%	95%	95%	74%	80%	99%	95%	88%	14%
p-, m-xylenes	>99%	94%	96%	81%	90%	95%	98%	92%	10%
ethylbenzene	>99%	94%	96%	72%	89%	93%	98%	90%	7%
4-ethyltoluene	>99%	80%	97%	100%	89%	100%	N.A.	N.A.	47%
toluene	>99%	52%	65%	79%	87%	98%	97%	91%	10%
benzene	>99%	66%	61%	78%	88%	84%	93%	N.A.	67%
acetone	80%	N.A.	83%	72%	86%	N.A.	100%	100%	9%

* Advertised removal is the removal efficiency stated by the manufacturer (Camfil) as a function of specific flow rate in the AHU, contact time and concentration of pollutant.
** average uncertainty calculated across shown removal efficiency measurements (two replicates for each measurement upstream and downstream the filters). Note that the concentrations downstream are, in some cases, close to or under the method detection limit, resulting in increased calculated uncertainty.

- Removal efficiencies of some particle-phase compounds have decreased from September 2018 – June 2019 (Table E2).

Table E2. Calculated removal efficiencies of particle-phase air pollutants.

Compound	Theoretical removal[#]	Phase II (Sept-2018)	Phase III (June 2019)
Black carbon	Not available	93% removal*	79% removal*
$PM_{2.5}$	>95%	90% removal	81% removal
PM_{10}	>95%	80% removal	54% removal
Coarse particles**	>95%	n/d	46% removal
Ultrafine particles	>98%	98% removal	96% removal

[#] theoretical removal estimates are calculated using equations from Azimi et al. (2014) for a MERV8 and MERV16 filter in series.
* average removal calculated with estimates of mixed air levels. Mixed air levels were estimated from measured outdoor and return air levels, weighted for outdoor air fraction. Outdoor air fraction was calculated from measurements of air temperatures made in outdoor air, return air, and mixed air. Presence of fans, surfaces introduce error to this calculation.
** coarse particles: particle with diameter between 2.5 μm and 10 μm. Note that the lower than theoretical removal of coarse particles is hypothesized to result from a source of coarse particles in the AHU downstream the filtration system, as discussed further in Section 3.3.

- Infiltration of traffic-related air pollutants across the building envelope appears generally low, based on an analysis of associations of traffic-related air pollutants measured inside the school with outdoor meteorological conditions.

1.2 Recommendations:

- Long-term reduction of student exposures to traffic-related air pollution at HTMS will require continuous attention to operation and maintenance of installed air treatment systems as well as consideration of administrative controls to reduce outdoor exposures to air pollution.
- We recommend that PPS continue to operate a network of PurpleAir sensors at the HTMS site, including a measurement at the school rooftop (outdoor air) and in selected locations throughout the school in order to inform filter change out schedule (Section 3.1.1).
- Timing and location of outdoor activities at HTMS should consider that measurements made on site indicate traffic-related air pollution is generally elevated in the morning hours and are highest in areas closest to I-5 (Section 3.1.3, Figure 11; Section 3.1.4; Section 3.2).
- We recommend that PPS establish a filter and carbon change out schedule that includes continued monitoring of particle and gas-phase removal efficiencies at quarterly frequency. We further recommend that the air handling unit be instrumented (or programmed, if instrumentation is in place) to measure pressure/flow across the air cleaning systems. These measurements will enable an informed and cost-effective filter and carbon changeout schedule to be developed (Section 3.3)
- We recommend that AHU air flows (design values and, if possible, values measured by the AHU) be made available to improve accuracy of the polar plot analysis of indoor air pollutant/meteorological relationships (Section 3.4). These data will enable more accurate assessment of infiltration of outdoor air pollution at the school.

2 Summary of approach

2.1 Background

In October 2017, the Portland Public School Board unanimously passed a board resolution (Resolution #5534) to re-open Harriet Tubman School as a middle school for Fall 2018. Harriet Tubman Middle School is located in the Eliot neighborhood (Albina District) just east of the I-5 North freeway (2231 N. Flint Ave), see Figure 1. This school is also in close proximity to several commercial and industrial facilities. The Portland Public School Board requested that a comprehensive health and safety assessment of Tubman middle school be conducted and be made available to the public.

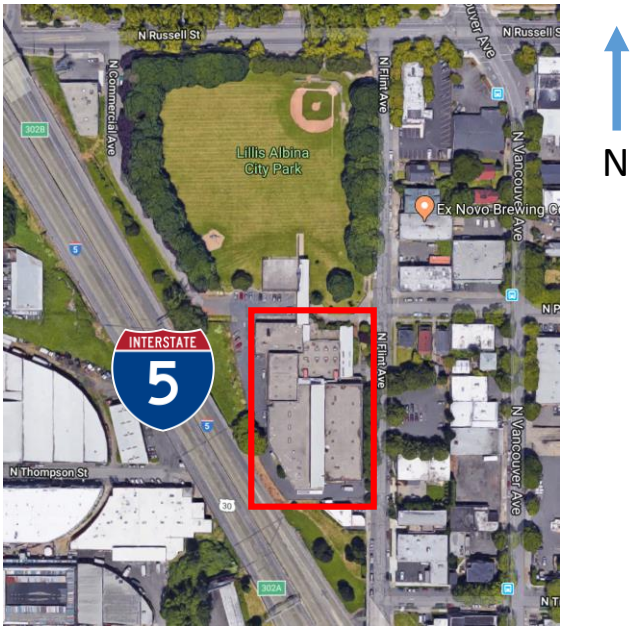

Figure 1. Location of Tubman Middle School (red outline) showing proximity of school to Interstate 5.

On January 8th, 2018, Portland Public Schools selected Portland State University to conduct monitoring and modeling to assess indoor and outdoor air quality conditions and site air flow conditions at Harriet Tubman Middle School. This project was conducted in three phases. Phase I objectives were to evaluate the outdoor air quality at the school site, to advise regarding the design of the building heating, ventilation and air conditioning (HVAC) system and building renovation, and finally to initiate the site model development for wind tunnel tests to characterize site airflows and possible outdoor air quality mitigation strategies. Phase II and Phase III air monitoring objectives were to characterize indoor and outdoor air quality at HTMS and evaluate the efficiency of the HVAC system following the renovation of the building (phase II) and after one school year of operation (phase III).

On April 18th, 2018, Portland State University released a Phase I report about outdoor air quality at Harriet Tubman Middle School with key recommendations for the HVAC system and building renovation. Key findings from the initial air monitoring campaign (Phase I report) were that, as anticipated, the site air quality is negatively impacted by its proximity to the freeway. Outdoor data show that there is a gradient of traffic related pollutants that decreases as a function of distance away from I-5 N, reaching background levels about 200-300 feet from the freeway. We also observed that air sampled on the SW side (freeway side) of Tubman Middle School is heavily impacted by freeway emissions while the E side (Flint Ave. side) is also impacted by freeway emissions but pollution is at a lower concentration.

Many air pollutants measured at Tubman during Phase I (Winter season) were elevated compared to Portland urban background site (DEQ SE Lafayette). However, criteria pollutants were below National Ambient Air Quality Standard (NAAQS) for the monitoring period. Toxic metals were below Oregon Ambient Benchmark Concentrations (except for Arsenic) while some toxic volatile organic compounds (acrolein, naphthalene, benzene) were above Ambient Benchmark Concentrations.

While the site is negatively impacted with respect to air pollution due to I-5, preliminary modeling showed that air pollutants of concern in HVAC outdoor ventilation air could be reduced to levels substantially below urban background and levels of health concern using commercially available air cleaning technologies.

Portland State University generated four key recommendations based on the findings and supporting data presented in phase I report:

- Student outdoor activities should be limited at HTMS, especially during high traffic periods. Outdoor air quality at the site is impacted by I-5 traffic and methods for reducing local outdoor urban air pollution levels are unlikely to reduce levels of air pollutants to values below urban background levels or Ambient Benchmark Concentrations.
- The HVAC system should be designed to include MERV16 filtration and dedicated sorbent beds capable of maintaining recommended media-air contact times for gas-phase pollutant removal.
- The HVAC system should be designed such that outdoor ventilation air intakes are sited as far from I-5 as possible. Indeed, phase I monitoring at HTMS indicated the site is impacted by emissions from the freeway and that levels of air pollutant are reduced with increasing distance from the freeway.
- The building should be commissioned with respect to HVAC balancing and building infiltration to ensure outdoor air enters the building via the dedicated outdoor air intake. It was recommended

that the building shell facing I-5 be weatherized (made airtight) and rooms facing I-5 be operated at slightly positive pressure.

One additional recommendation was to monitor efficacy of the air cleaning system periodically for breakthrough of gas-phase compounds and confirmation of removal efficiency of particulate matter.

The summary of the phase I air quality monitoring conducted at Harriet Tubman Middle School was that **ambient air quality is heavily impacted by freeway emissions and occupants of the building must be protected from traffic-related air pollutants. The phase II and III described here were designed to assess the efficacy of the HVAC system and the building renovation after installation and commissioning of the system (phase II) as well as after one school year of operation with normal occupancy (phase III).**

2.2 Objectives of Phase II and Phase III air monitoring at HTMS

Phase II and Phase III of the air monitoring project at HTMS include the following goals:

1.) Measure exposure concentrations of air pollutants of concern (traffic-related air pollutants as well as some criteria air pollutants) inside HTMS.
2.) Measure exposure concentrations and spatial variability of air pollutants of concern in the near-vicinity of HTMS.
3.) Test the efficiency of the newly installed heating, ventilation and air-conditioning (HVAC) system to remove traffic-related air pollutants from building supply air, initially and after one school year.
4.) Evaluate the potential for infiltration of traffic-related air pollution across the building envelope.

Data collected in Phases II and III support exposure modeling and health assessments conducted by Dr. William Lambert. Summarized data reported to Dr. Lambert in support of this assessment are provided in section 5.1.2.

The data collected in support of these four objectives also enable recommendations to be made regarding operation and maintenance of installed air treatment systems, summarized in the executive summary section of this document, and described in greater detail in subsequent sections.

2.3 Rationale for Phase II & III deployment at HTMS

Portland State University conducted site visits at Harriet Tubman Middle School with the contractors in July 2018 and in March 2019 to evaluate the needs for air quality equipment (locations, power outlets, sampling lines, site access, etc.) and to verify the functionality of the new HVAC system for mitigating

student exposures to air pollution. While the previous ventilation system was installed on the south side of the building, following the recommendations from phase I the new HVAC system was installed further from I-5, on the north side of the building (Figure 2) by PPS contractors. Note that the outdoor air sampling associated with the renovation of the building HVAC system is in the near vicinity of this outdoor air intake (i.e., located within the red box shown in Figure 2, right)

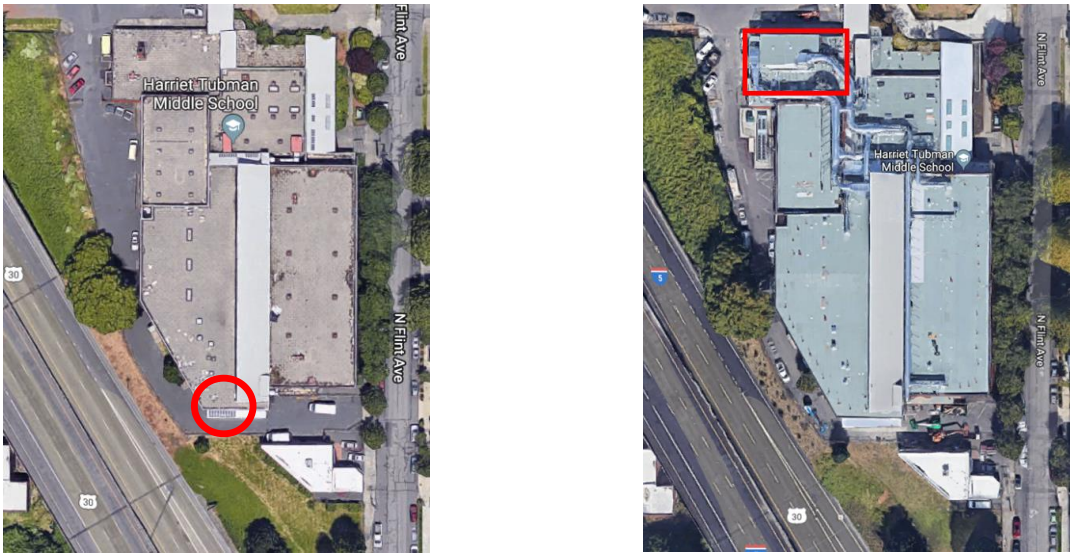

Figure 2. Left: Approximate location of a previous ventilation intake on HTMS building, in close proximity to I-5 (Phase I). Right: Location of the new HVAC system at Tubman Middle School, further from the I-5 (Phase II & III). Note that the new HVAC system (shown in right) serves the entire HTMS building.

Two sets of monitoring instruments were deployed directly into the HVAC system air handling unit (AHU) (Figure 3). One of the two sets was deployed with a switching valve system allowing for the monitoring of air pollution levels at two locations. This deployment allowed us to perform air pollutants measurements in three different locations: return air (RA) also called indoor air (in AHU-1, A on Figure 3), supply air (SA) (cleaned air) (in AHU-5, B on Figure 3), and outdoor air (OA) (on the rooftop, C on Figure 3). The rationale for the choice of these locations was as follows. First, the return air samples enabled time-series, spatially-integrated indoor air quality levels to be determined. This is because the AHU serves the entire school, thus the return air is the location that allows the broadest characterization of air pollution levels in the school to be made. Second, outdoor air pollution levels were monitored to enable us to understand indoor-outdoor air pollution relationships, as well provide a general estimate of outdoor air pollution conditions at the school. Finally, the supply air provides a measurement of the levels of air pollutions in air treated by filtration and sorbent cleaning systems in the AHU. We could not measure mixed air (MA) levels, as our instrumentation enabled us to make measurements at only three locations. We chose not to measure this

location as levels of air pollution in MA can be calculated by knowing the airflow rates of return air and outdoor air (where air quality measurements were made), and making mixing calculations accordingly. To date, we have not been able to obtain this flowrate information from the mechanical contractor; instead, we have estimated MA levels using the fraction of outdoor air in mixed air using measurements of temperature made in return air, outdoor air, and mixed air.

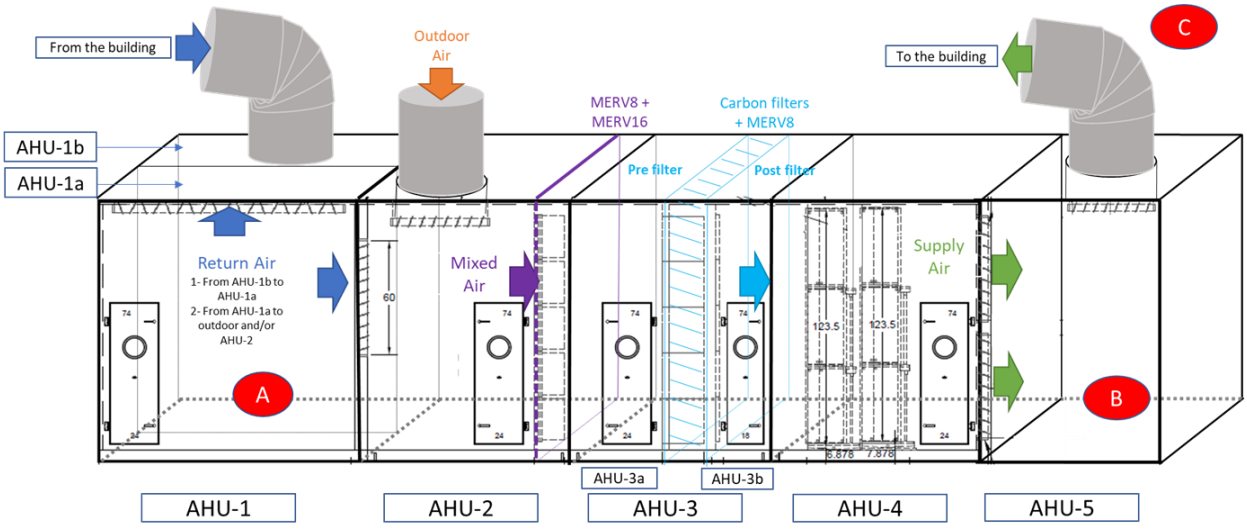

Figure 3. Schematic of the Air Handling Unit (AHU). Air coming back from the building (return air or indoor air, air to which students and staff are exposed) enters in AHU-1b and is then directed to AHU-1by a bank of four fans. Depending of the time of the day, return air (RA) is then exhausted from AHU-1a to outside and / or directed to AHU-2 where it is mixed with outdoor air coming from the penthouse on the rooftop. Mixed air (MA) is then directed through MERV8 and MERV16 filters to AHU-3. In AHU-3, post particle filtration, mixed air is sent through carbon filters for gas phase compounds removal and sent to AHU-4 (supply air) with the heating/cooling system. The heated or cooled supply air (SA, cleaned air) is finally sent to AHU-5 where it is sent to the building by a bank of four fans and supply air ducting. The two sets of instruments were deployed in location A (RA) and location B (SA). A switching valve system was installed allowing for outdoor air (OA) measurements in location C.

On the rooftop, PSU deployed a weather station to characterize meteorological conditions on site by monitoring wind direction, wind speed, temperature, relative humidity, and barometric pressure. Measurement of these parameters provides context for assessing the origin of air pollution by evaluating time-series data of air pollution and meteorological conditions. Pictures of the weather station deployed on the rooftop of Harriet Tubman Middle School during phase II and III are shown in Figure 4.

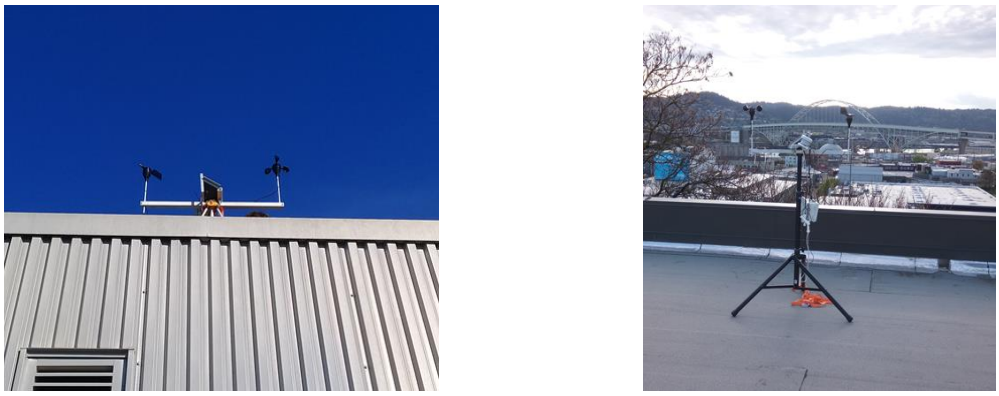

Figure 4. Left: Installation of weather station on HTMS rooftop during phase II. Right: the same weather station installed on HTMS rooftop during phase III (location more accessible after renovation).

PSU also made measurements using portable air pollution monitors to create spatial maps of traffic-related air pollutants in the vicinity of the school building (see Section 3.2). These spatial mapping efforts focused on measurements of ultrafine particles made with a condensation particle counter and handheld GPS device.

Inside the school and at several outdoor locations (rooftop and at a nearby basketball court where children play), PSU deployed a network of low-cost air pollution sensors (PurpleAir PA-II SD) which enabled measurement of particulate matter in the size range of 0.3 – 10 micrometers. These measurements provided an assessment of the efficacy of the air treatment systems at specific locations throughout the school to complement the more detailed, but spatially integrated measurements made in the AHU return air. These sensors were also used to inform the exposure assessment by providing a measurement of exposure concentrations of $PM_{2.5}$ and PM_{10} in an outdoor location frequented by students (at the basketball court).

Finally, air pollutant concentrations of traffic-related air pollutants or other air pollutants measured at HTMS were collected from various regulatory monitoring sites around Portland to provide context to the data collected at HTMS. These additional efforts are discussed in further detail and results presented in this report.

2.4 Deployment schedule

Table 1 summarizes the deployment of monitors to the Harriet Tubman Middle School for indoor and outdoor air monitoring during phase II and Table 2 summarizes the deployment of monitors during phase III. A more detailed description of instrument manufacturer and model is provided in Table 3. A summary of the quality assurance/quality control plan is provided in Table A1 in Section 5.2.

Table 1. Summary of deployment schedule for Phase II monitoring at Harriet Tubman Middle School. The presence of confounders (wildfire smoke events, ongoing presence and usage of diesel construction equipment, construction/renovation/cleanup inside and outside of building) prevented measurement of meaningful results in September 2018. Therefore, only the results from October 2018 are shown in this report.

		Aug-18		Sep-18				Oct-18		
		Week 0	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Confounders	Works inside and around the school									
	Woodsmoke on Portland area									
	Tuning/balancing of the Air Handling Unit (AHU)									
Air Monitoring	Co-location of two sets of instruments in the same room (221)									
	Indoor and AHU sampling with presence of confounders									
	Indoor and AHU sampling post-confounders									
	Outdoor air gradient sampling									
	PurpleAir Sensor Network									

Table 2. Summary of deployment schedule for Phase III monitoring at Harriet Tubman Middle School.

	Apr-19			May-19				Jun-19		
	Week 0	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9
Weather station - Rooftop										
AHU sampling										
Purple Air Sensor Network										
Passive sensor - NO2										
VOCs sampling - real time (PTR-TOF-MS)										
VOCs sampling (TD-GC-MS)										

end of campaign end of schoolyear

2.5 Monitors employed in Phase II & III monitoring at HTMS

This section summarizes the monitoring devices deployed and used in the characterization of air quality at Harriet Tubman Middle School during phase II & III. Figure 5a-d provide pictures of the monitors used and the nature of their installation.

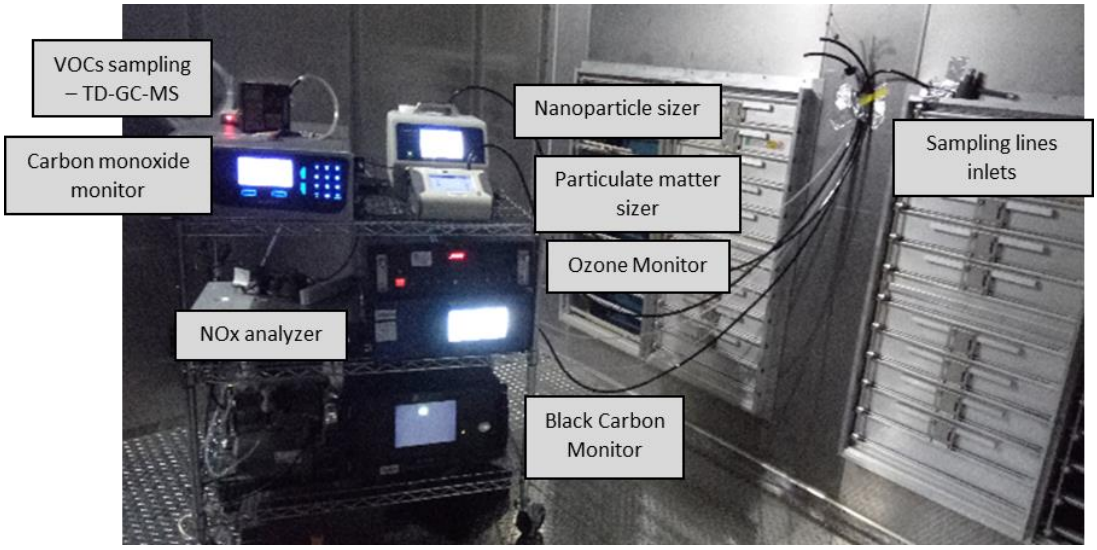

Figure 5a. Installation of one set of instruments in the AHU-1 at Harriet Tubman Middle School

Figure 5b. Installation of a second set of instruments in the AHU-5 at Harriet Tubman Middle School. The instruments deployed here are the same as the instruments of figure 5a. Note that this collection of instrumentation included a switching valve system that enabled measurements to be made in both the supply air and outdoor air.

Figure 5c. Volatile Organic Compound (VOCs) monitoring systems. The PTR-TOF-MS (picture on the left) in AHU-5 and sampler and sorbent tubes for GC-MS (picture in the middle) in AHU-3 (pre carbon filter) at Harriet Tubman Middle School. TD-GC-MS in the lab at PSU for the analysis of sorbent tubes (picture on the right).

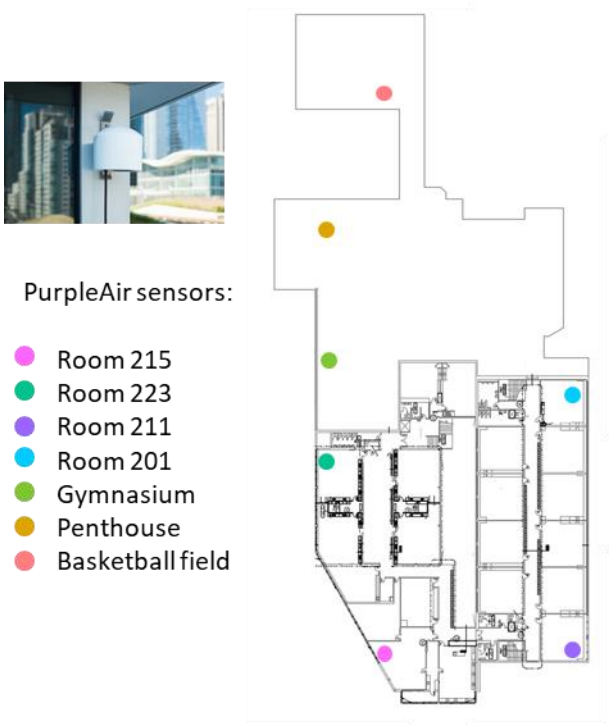

Figure 5d. PurpleAir sensors network at Harriet Tubman Middle School. PurpleAir sensors measure particulate matter ($PM_{1.0}$, $PM_{2.5}$, PM_{10}). Sensors were installed inside the building except for the penthouse (roof of the building) and basketball field, these two sensors were placed outside the building.

Table 3. Summary of monitors deployed at Harriet Tubman Middle School.

Parameters Monitored	Instrument Manufacturer/Make	Method of measurement
Nitrogen oxide, nitrogen dioxide	Teledyne T200P Teledyne T200UP	Chemiluminescence detection; concentration range: 0-20 ppb to 0-20 ppm
Carbon monoxide	Ecotech Serinus 30	Non-Dispersive Infrared Spectrophotometry (NDIR); concentration range: 0-200 ppm, detection limit 40 ppb
Black carbon	Magee Scientific AE33	Analysis of the aerosol particles by measuring the transmission of light through the portion of the filter tape containing the sample versus the transmission through the portion acting as a reference area; concentration range: 0.01 to 100 µg/m^3
PM 1, 2.5, 10 continuous	PurpleAir sensors	Laser particle counters
PM (OPS)	TSI 3330 OPS	Optical scattering from single particles; size range: 0.3 to 10 µm; concentration range: 0 to 3,000 particles/cm^3
UFP (SMPS)	TSI 3910 NanoScan	Scanning Mobility Particle Sizer; size range: 10 to 420nm; concentration range: 100 to 1,000,000 particles/cm^3
UFP mobile transects	TSI PTrak	Condensation Particles Counter; size range: 20 to 1000 nm; concentration range: 0 to 50,000 particles/cm^3
Nitrogen dioxide passive samples	Ogawa samplers	Chemical (TEA) reaction with NO_2
Volatile organic compounds continuous	Ionicon PTR-TOF-MS	Proton Transfer Reaction Mass Spectrometry with Time-Of-Flight analyzer; limit of detection = 10 pptv
Volatile organic compounds	AirToxic glass sorbent tubes + Agilent TD-GC-MS	Compounds trapped on sorbent tubes, desorption in gas chromatography coupled with Mass Spectrometry
Site meteorology/weather	HOBO Onset	Measurement of temperature, relative humidity, wind direction, wind speed

3 Results & Discussion

3.1 Objective 1: Estimate exposure concentrations of air pollutants at HTMS

During phase II (Aug – October 2018) and phase III (April – June 2019), black carbon (BC), carbon monoxide (CO), ultrafine particles (d<100nm, also referred to as UFP), $PM_{2.5}$, PM_{10}, several volatile organic compounds, and nitrogen oxides (NO, NO_2) were monitored continuously from the Tubman Middle School Air Handling Unit (AHU) as described in section 2.2. Meteorological parameters were also monitored during these periods on the roof of the building. Figure 6 shows the wind pattern during the two monitoring periods of Phase II and Phase III. During Phase II, with data reporting focusing on October of 2018, the predominant winds were from the NW while during Phase III, occurring during May-June of 2019, the predominant winds were from the NW and SE. Meteorological conditions (wind speed and wind direction) at Tubman site help to better understand pollution sources and levels. As will be discussed subsequently, site meteorology is an important driver of air pollution levels at HTMS. In general, wind directions that result in the school being placed downwind of I-5 (southwesterly to northwesterly) result in elevated levels of traffic-related air pollution at the site. Figure 6 shows a larger proportion of periods with these wind directions occurred in the Phase II campaign occurring in the Fall season.

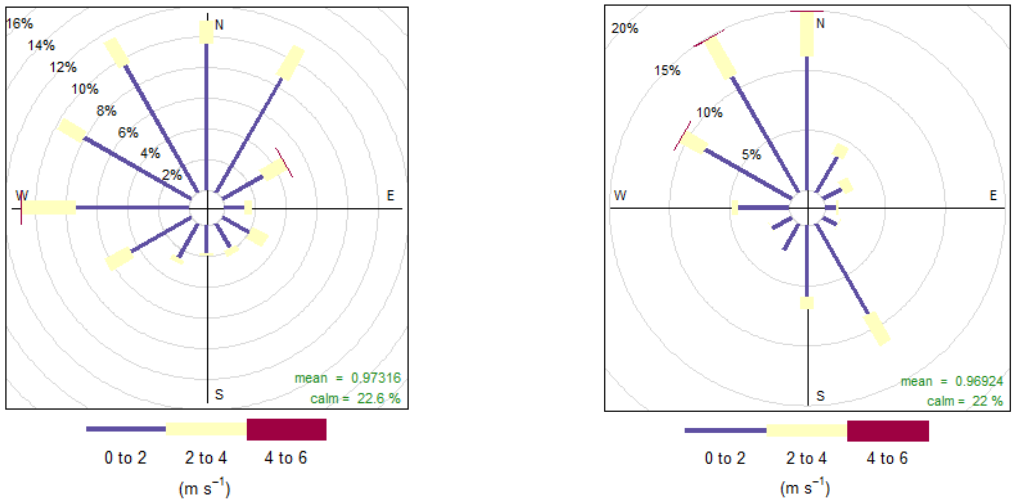

Figure 6. Frequency of wind counts by direction (%) during school time (9 AM to 4 PM, weekdays only). Left: Phase II in October 5-19th, 2018; Right: Phase III in May-June 18th, 2019.

Phase II started a week before the start of the school year while some construction and renovation operations were still occurring. Further, outdoor air quality conditions were substantially degraded due to persistent wildfires occurring during September of 2018. Therefore, the presence of confounders (e.g., we observed ongoing presence and usage of diesel construction equipment, construction/renovation/cleanup inside and

outside of building and also advisories for and visible wildfire smoke events) reduced our ability to generate conclusions regarding ambient air pollution impacts to the school under "normal" conditions. Thus, only the results from October 2018 will be shown for phase II.

3.1.1 Particle-phase monitoring

Black carbon (BC), $PM_{2.5}$, PM_{10} and ultrafine particles (UFP) are particle phase traffic-related air pollutants. Of these particle-phase air pollutants, black carbon and ultrafine particles (particles with diameter < 100 nm) are often used as indicators of a traffic source as they derive from combustion processes (Cyrys et al. 2003). Black carbon is the solid carbonaceous soot present in particulate matter mass that is comprised a mixture of organic compounds, including polycyclic aromatic hydrocarbons of health concern ("Diesel Exhaust: Critical Analysis of Emissions, Exposure, and Health Effects" 1995). Ultrafine particles are those particles with diameter smaller than 100 nanometers, of which motor vehicles are a prominent source (Zhu et al. 2002). While there exist secondary sources of ultrafine particles, motor vehicles have been shown to be the primary source of ultrafine particles in urban environments (Morawska et al. 2008). Levels of these pollutants were monitored during Phase II and III in order to evaluate students and staff's exposure concentrations. Average concentrations in outdoor air, return air (indoor air), and supply air were calculated for the school period corresponding to a time frame from 9 AM to 4 PM from Monday to Friday (Figure 7a-d.).

Figure 7a-d clearly shows that outdoor levels are higher than indoor levels during the school period, especially for black carbon and ultrafine particles. This finding indicates that the school building and HVAC system are protective for students and staff from air pollution present in outdoor air at the school. Indoor levels appear to be lower than the NAAQS values (National Ambient Air Quality Standards) or the Oregon ABCs (Ambient Benchmark Concentrations) when available; however, a health exposure assessment is not the subject of this report, PPS retained the services of an environmental health scientist (Dr. William Lambert) who used data reported here to assess implications of exposures to indoor and outdoor levels of air pollution at HTMS.

We also observed lower outdoor concentration during phase III compared to phase II concentration, partially explained by the meteorological conditions (Figure 6), with higher wind speed and greater atmospheric mixing height during phase III leading to higher dilution of pollutants. The outdoor environment is an important source of air pollution to the indoor environment; thus, we observe that indoor (return) air levels show similar trends with generally lower levels in Phase III compared to Phase II. In the case of PM_{10} indoor levels, we see higher indoor concentrations in Phase III, which we attribute to the fact that there are exist indoor sources of PM_{10} such as human activities that could lead to these results that are likely to be variable across the school year. Slightly higher supply (cleaned) air levels were observed for

particulate-phase compounds during phase III, likely due to a decrease of the removal efficiency of the MERV filters in the AHU. Trends in measured air pollution removal efficiency is explored in greater detail in Section 3.3.

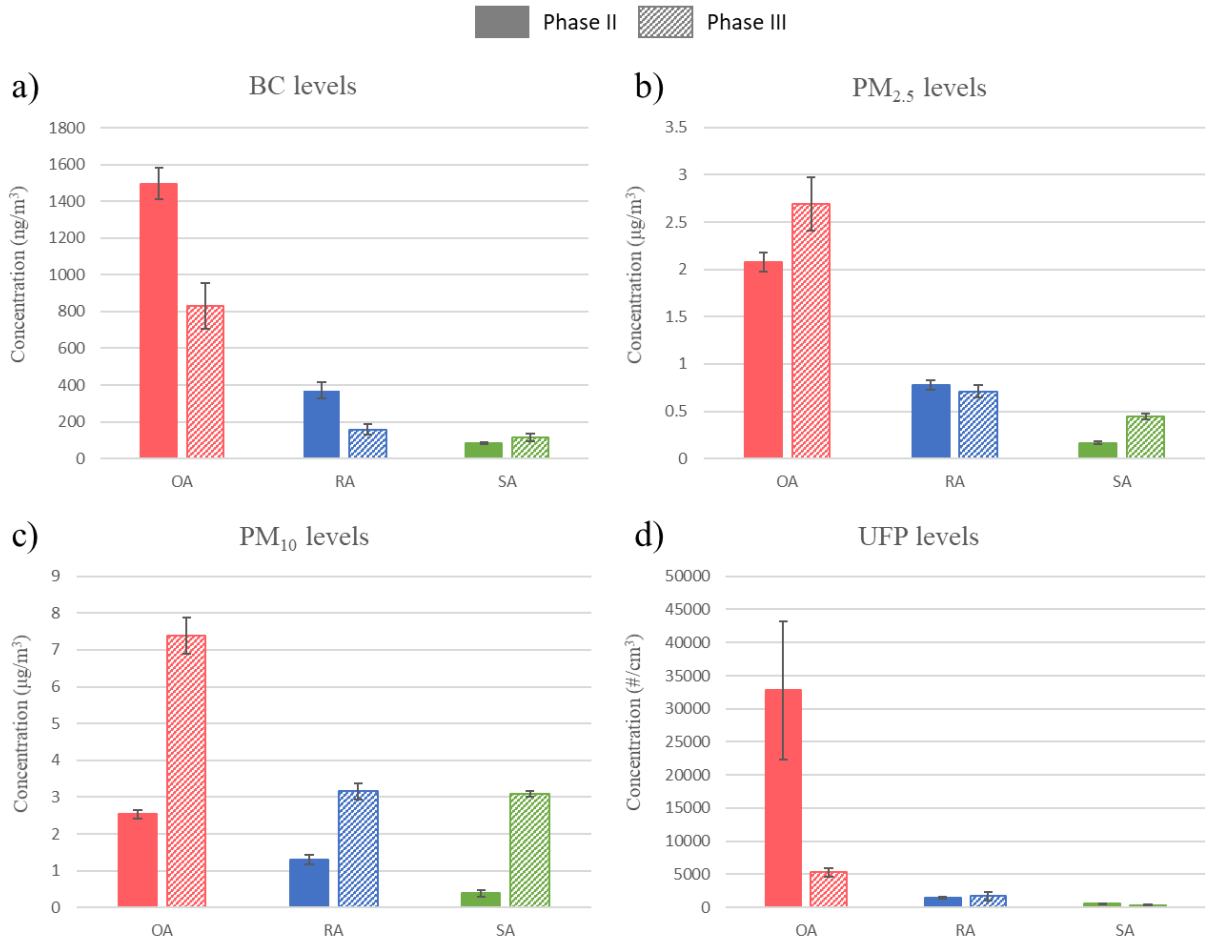

Figure 7. Average concentrations of a) black carbon (BC), b) $PM_{2.5}$, c) PM_{10}, and d) ultrafine particles (UFP) during school period for each location (OA: outdoor air in red, RA: return air or indoor air in blue, SA: supply air in green) and each phase (solid bars: phase II, hatched bars: phase III). Note that these data are averaged over a school period, defined as 9 AM to 4 PM from Monday to Friday.

Additional low-cost sensors (PurpleAir PA-II SD) monitored $PM_{1.0}$, $PM_{2.5}$ and PM_{10} in seven locations within the school (see Figure 5d): four classrooms (R201, R211 facing Flint avenue; R215, R223 facing I-5), the gymnasium, and two outdoor locations (the penthouse, corresponding to the outdoor air intake of the AHU, and the basketball court). Average concentrations of the seven locations were calculated for the school period (Figure 8a-c.).

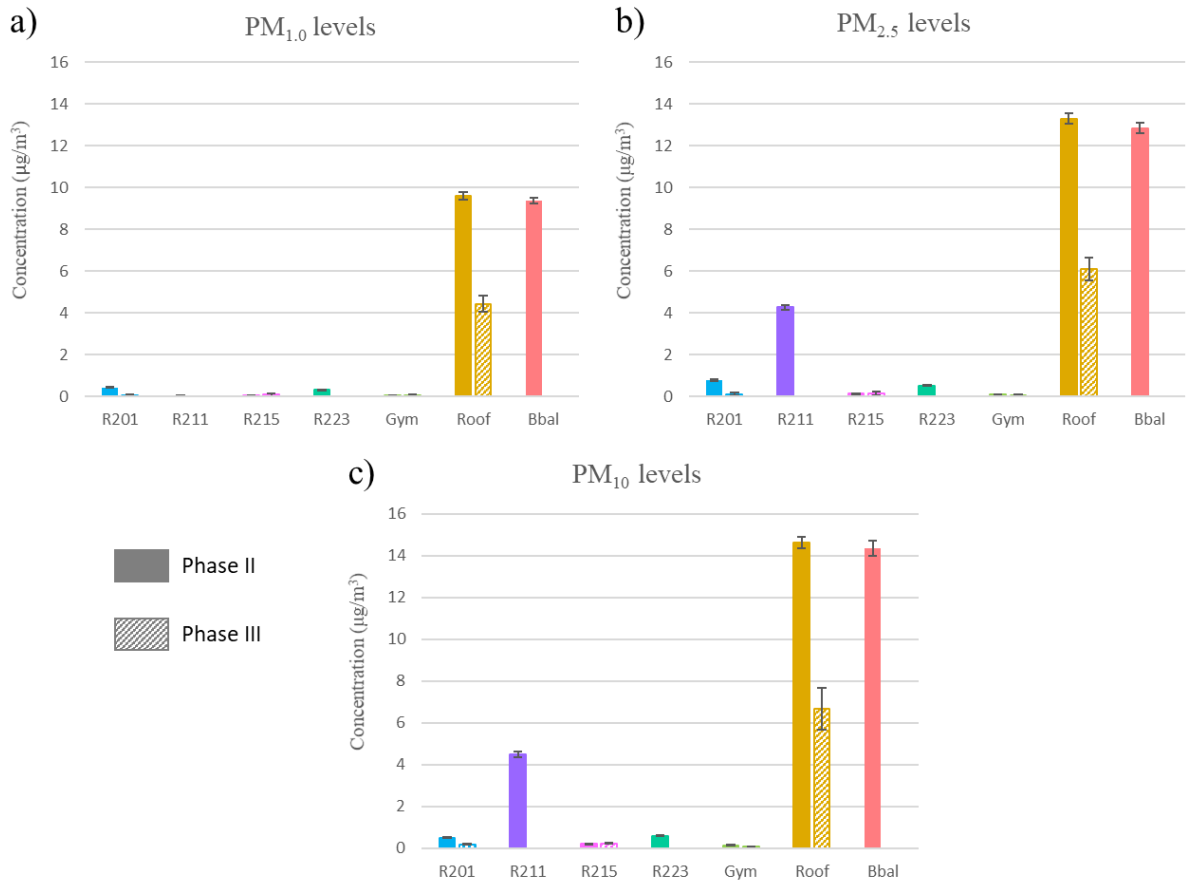

Figure 8. Average concentrations of a) $PM_{1.0}$, b) $PM_{2.5}$, and c) PM_{10} during school period for each location (R201 in blue, R211 in purple, R215 in pink, R223 in blue-green, Gym (gymnasium) in green, Roof (penthouse) in yellow, and Bbal (basketball field) in red) and each phase (solid bars: phase II, hatched bars: phase III). No data were collected during phase III for R211, R223 and basketball filed due to some issues with the sensors.

As expected and similar to the findings shown in Figure 7, levels in the fours classrooms and the gymnasium were low compared to outdoor levels (roof and basketball field) (Figure 8a-c), indicative of removal of particles in the filtration system installed in the school HVAC system. Higher levels were observed in the classroom 211 (South-Flint side) during phase II for $PM_{2.5}$ and PM_{10} but not for $PM_{1.0}$. We speculate that this elevation of larger particles in classroom 211 is due to a relocation occurring in this classroom at the beginning of the school year during which relocation activities (moving of equipment and furniture, occupant activities, etc.) contributed to elevated concentrations of larger particles originating from the indoor space.

While the PurpleAir sensors do not provide an optimal proxy of traffic-related air pollution, they provide a useful, rapid indicator of the general efficacy of the particle air cleaning systems in the school. Furthermore, due to their low-cost and ease of operation, they can be installed at multiple locations throughout HTMS to provide spatial coverage of indoor-outdoor particle relationships at the school. These tools may also provide opportunities for outreach and engagement with science classes and with parents interested or concerned about air pollution at HTMS. **Thus, we recommend that PPS continue to operate a network of PurpleAir sensors at the HTMS site, including a measurement at the school rooftop and in selected locations throughout the school.** In addition to comparing relative levels (e.g., indoor vs. outdoor, or tracking particle levels through time), PurpleAir sensors have been shown to provide useful quantitation of magnitudes of particulate matter levels (Singer and Delp 2018).

Exposure concentration of particle phase traffic-related air pollutants are summarized in appendices (Table A1).

3.1.2 Gas-phase monitoring

Carbon monoxide and nitrogen oxides are gas phase traffic-related air pollutants. In the past several decades, ambient levels of these compounds have decreased substantially in urban air and are generally not present in urban environments as single components that are elevated above established health thresholds (e.g., the National Ambient Air Quality Standards). However, these compounds continue to be monitored and have been shown to be useful proxies for exposure to traffic-related air pollution, though it is unlikely that there exists a single, ideal proxy for TRAP exposure (Levy Ilan et al. 2014). For example, in a previous study, elevated levels of carbon monoxide and oxides of nitrogen have been associated with the prevalence of asthma in middle school student populations (Guo Y L et al. 1999). Levels of these pollutants have been monitored and average concentrations in outdoor air, return air (indoor air), and supply air are reported in Figure 9a-c. for the school period.

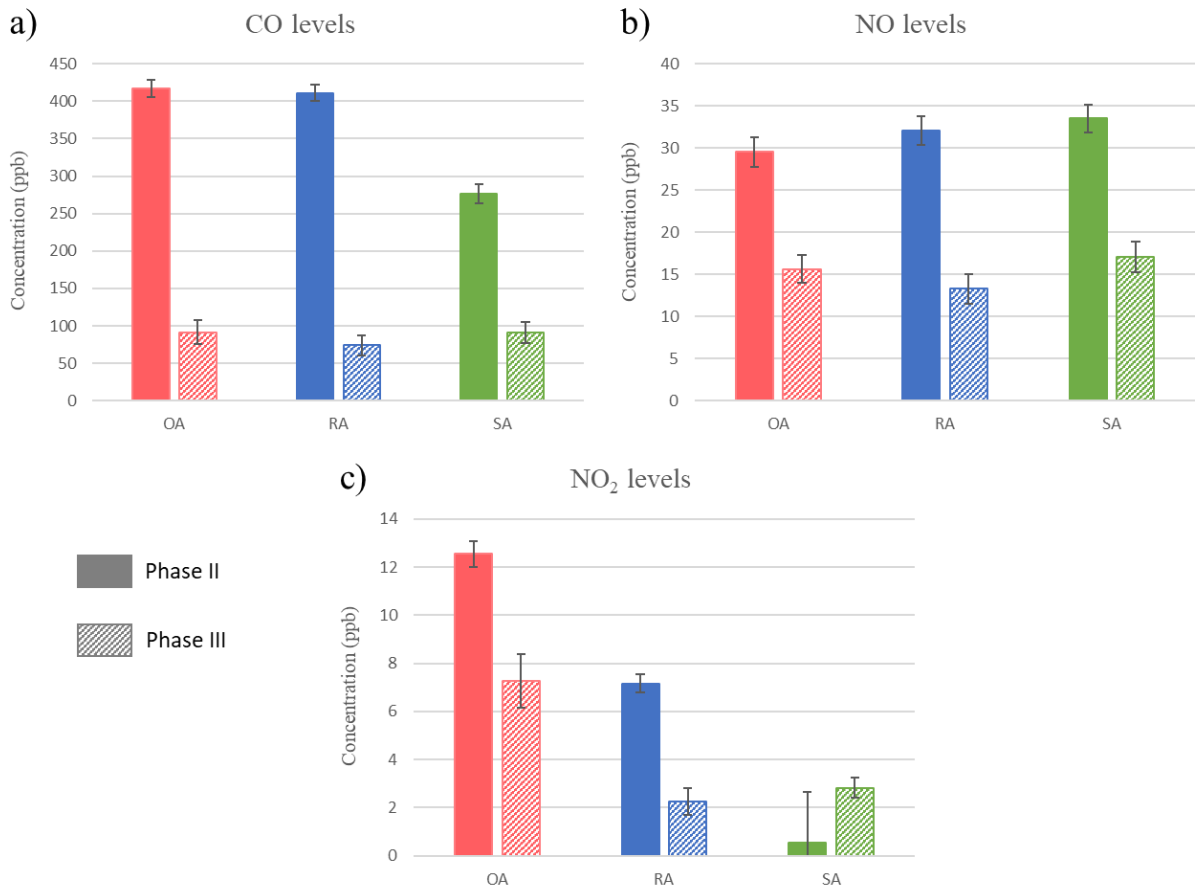

Figure 9. Average concentrations of a) carbon monoxide (CO), b) nitrogen monoxide (NO, also called nitric oxide), and c) nitrogen dioxide (NO_2), during school period for each location (OA: outdoor air in red, RA: return air or indoor air in blue, SA: supply air in green) and each phase (solid bars: phase II, hatched bars: phase III).

Figure 9a-c clearly shows lower concentrations of CO, NO, and NO_2 during phase III compared to phase II, partially explained by the meteorological conditions (Figure 6), with higher wind speed and mixing height during phase III leading to a higher dilution of pollutants. An additional explanation is that after one school year, the AHU was optimized and construction works and relocation activities near the school were completed (recall that during phase II, we observed periods where diesel trucks and construction equipment were operating on the school grounds). Levels of carbon monoxide (Figure 9a) and nitrogen monoxide (Figure 9b) are similar for outdoor and indoor. This result is expected as the AHU carbon filters are not designed to remove these two pollutants. Also note that these pollutants are present at low levels (e.g. carbon monoxide highest level is 420 ppb while the NAAQS is 9,000 ppb for 8 hours and 35,000 ppb for 1 hour; nitrogen monoxide highest level is 34 ppb while the OSHA, Occupational Safety and Health Administration, set the limit at 25,000 ppb over 8 hours).

Exposure concentration of gas phase traffic-related air pollutants are summarized in appendices (Table A2).

The determination of volatile organic compound (VOC) concentrations was performed using two different methods: gas chromatography coupled with mass spectrometry (GC-MS) (phase II and III) and proton transfer reaction – time of flight - mass spectrometry (PTR-TOF-MS) (phase III only). The second method (PTR-TOF-MS) was used here for the temporal variation of VOCs while TD-GC-MS method to assess the average concentrations of VOCs.

For the GC-MS (Agilent Technologies), VOCs have been sampled with sample tubes containing two different sorbents. For each sample tube, samplers ran for ten occurrences, for sixteen minutes each occurrence, within a seven-hour period. The sample flow rate was 25 mL/min. During Phase II, seven VOCs samples were taken on weekdays in the timeframe of 9 AM to 4 PM between September 18th and October 10th and five samples on the same timeframe between April 18th and June 18th during phase III. The PTR-TOF-MS is a real-time method that was deployed with a custom switching valve apparatus that enabled measurements of VOCs to be made in the return, supply, and outdoor air via sampling lines run through the air handling unit.

Table 4. Summary of VOCs concentrations at Harriet Tubman Middle School during the school period (average on 7 replicates for phase II and 5 replicates for Phase III, sampling on weekdays from 9 AM to 4 PM).

Chemical name	Sources *	ABC# ($\mu g/m^3$)	Phase II OA ($\mu g/m^3$)	Phase II RA ($\mu g/m^3$)	Phase II SA ($\mu g/m^3$)	Phase III OA ($\mu g/m^3$)	Phase III RA ($\mu g/m^3$)	Phase III SA ($\mu g/m^3$)
benzene	burning of coal and oil, gasoline service stations, and motor vehicle exhaust	0.13	0.24**	0.21**	0.09**	0.11**	0.06**	0.05**
1,3-butadiene	motor vehicle exhaust	0.03	traces	traces	traces	traces	traces	traces
chloroform	manufactory, swimming pools, pulp and paper mills, hazardous waste sites, sanitary landfills	300	0.06	0.10	0.08	0.08	0.08	0.08
n-hexane	used as solvent to extract edible oils, used as solvent for glues, varnishes, inks	7000	0.27	4.20	4.10	0.74	1.16	1.68
naphthalene	burning of coal gas, diesel and oil, use of mothballs, some manufactory	0.03	0.30	0.56	0.10	0.10	0.06	0.02
tetrachloroethylene	used for dry cleaning and textile processing, as a chemical intermediate, and for vapor degreasing in metal-cleaning operations	35	0.24**	0.12**	0.18**	0.05**	0.04**	0.03**
toluene	automobile emissions, paints, adhesives, cigarette smoke	5000	1.15	2.75	0.54	0.41	0.18**	0.10**

Table 4 (continued). Summary of VOCs concentrations at Harriet Tubman Middle School during the school period (average on 7 replicates for phase II and 5 replicates for Phase III, sampling on weekdays from 9 AM to 4 PM).

Chemical name	Sources *	ABC[#] (µg/m^3)	Phase II OA (µg/m^3)	Phase II RA (µg/m^3)	Phase II SA (µg/m^3)	Phase III OA (µg/m^3)	Phase III RA (µg/m^3)	Phase III SA (µg/m^3)
trichloroethylene	industrial degreasing operations	0.2	0.04**	0.05**	0.16	0.03**	traces	traces
m- & p-xylenes	industrial sources, auto exhaust	200 (mixed)	1.10	14.01	0.16	0.31	0.10	0.03
o-xylene	industrial sources, auto exhaust		0.42	4.75	0.07	0.11	0.04	0.01
styrene	Production of polystyrene plastics and resins	1000	0.09	0.12	0.01**	0.03	0.04	0.01**
ethylbenzene	gasoline, pesticides, solvents, carpet glues, varnishes, paints, and tobacco smoke	0.4	0.34	7.60	0.09	0.08	0.03	0.01
trimethylbenzene (1,3,5-)	Additive and component of some aviation gasoline blends, component of coal tar	NA	0.16	0.28	0.02	0.04	0.03	0.01
Ethyl toluene	used for the production of specialty polystyrenes.	NA	0.21	0.36	0.01**	0.05	traces	traces
methyl ethyl ketone	used as a solvent in processes involving gums, resins, cellulose acetate, and cellulose nitrates	NA	0.25	1.95	0.23	0.24	0.16	0.07

* from various U.S. EPA resources

** concentrations under the method detection limit (Table A5)

[#] Oregon Ambient Benchmark Concentration 2018

NA: Not available

"Traces" means the value is under the detection limit of the instrument.

Values in red are those elevated above Oregon ABCs. Confer table A5 in appendices for the method detection limits and analytical precision.

There exist many VOCs in urban air (Yuan et al. 2012). A subset of the categorization of VOCs is BTEX (for benzene, toluene, ethylbenzene, xylenes) which are VOCs which are observed to be elevated in vehicle exhaust (Buczynska et al. 2009). While we collect and report data on the analysis of a broader set of VOC data (Table 4), some analyses (e.g., analysis of diurnal trends) focuses on results for BTEX and several other compounds also generally known to be elevated as a result of vehicle traffic.

Figure 10a-b shows the average concentration of BTEX in outdoor return (indoor) and supply air during phase II and III. In general, it should be noted that the values of toluene, ethylbenzene and xylenes (TEX), in return (indoor) air during phase II decreased with time e.g., ethylbenzene $23 \rightarrow 2.8 \rightarrow 0.3$ $\mu g/m^3$ across 3 weeks (Figure 10a). We speculate that this due to the renovation of the building (paint, adhesives, etc. are known sources of TEX) and also the presence of new materials (e.g., furniture, building materials) that may emit TEX (Brown 2002; Huang et al. 2011; Jones 1999). Prior studies have shown that many VOCs (including toluene) are emitted into a building following renovation, subsequently decreasing over the course of weeks to months (Herbarth and Matysik 2010; Yura, Iki, and Shimizu 2005). Their concentrations dramatically decreased during the few first weeks to reach lower and stable levels that can be seen after one school year of operation (Figure 10b). In addition, while benzene, ethylbenzene and naphthalene were elevated above the ABC levels during phase II, only naphthalene remains elevated above the Oregon ABCs levels in outdoor air and indoor air during phase III (Table 4) with lower levels than during phase II.

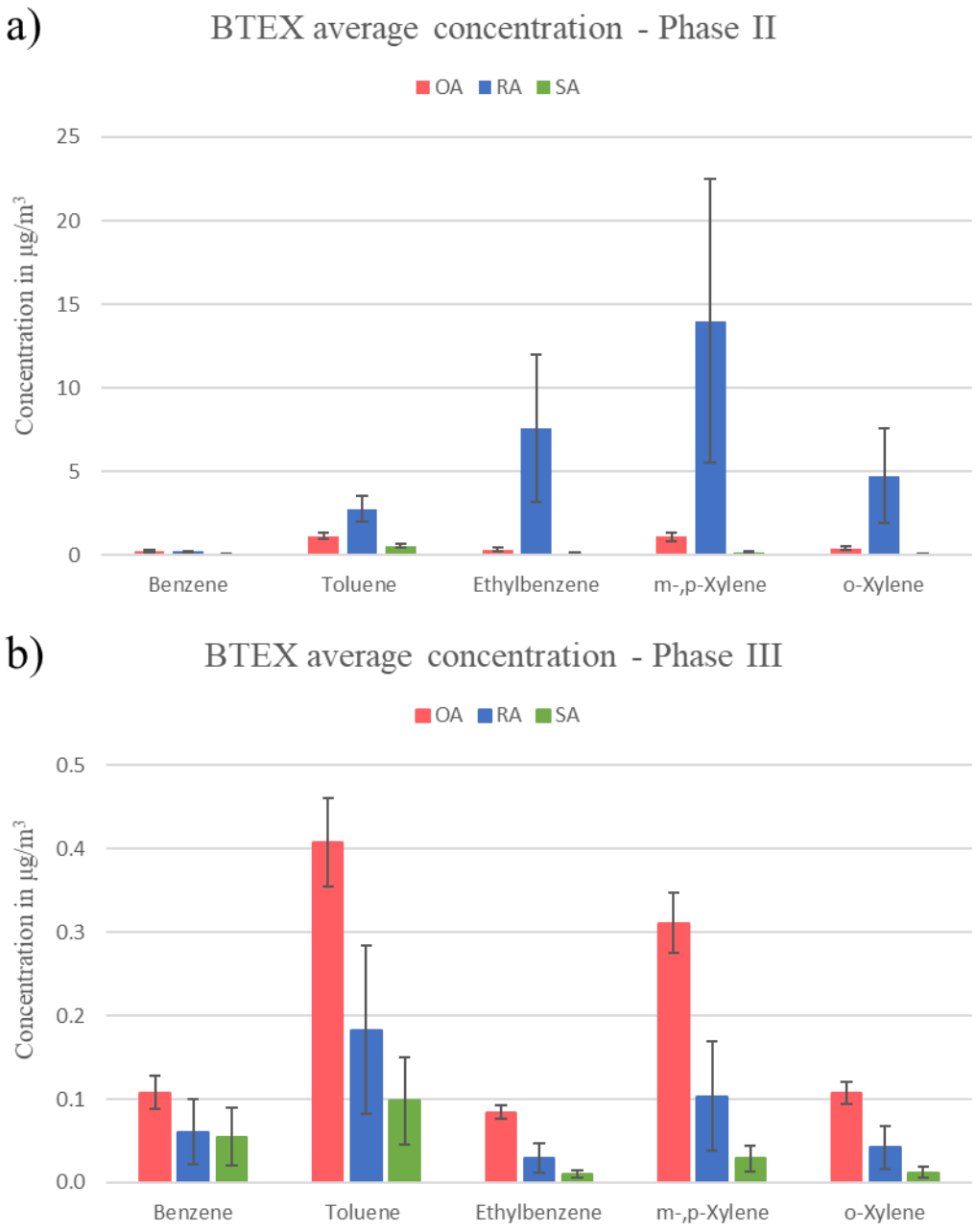

Figure 10a-b. Average concentrations of BTEX a) over seven replicates during phase II, and b) over five replicates during phase III, during school period for each location (OA: outdoor air in red, RA: return air or indoor air in blue, SA: supply air in green).

Exposure concentration of volatile organic compounds other than BTEX are summarized in Table 4 and appendices (Table A3).

3.1.3 Temporal variation of pollutants

We examined the temporal variation of pollution levels with respect to time of day and day of week. Similar trends were observed during phase II and phase III, therefore, only data from phase III are presented here. Figure 11 shows a pattern consistent with a traffic-related pollutant for outdoor air (OA in red) with elevated levels during morning rush hour for black carbon and ultrafine particles. Note that associations with morning rush hour are not apparent for $PM_{2.5}$ and PM_{10}, due to their contribution from a wider variety of sources than traffic-related air pollution. In blue, return air (or indoor air) clearly shows a pattern consistent with AHU operation with a "U-shape" curve apparent for traffic-related air pollutants between 6 AM and 6 PM on weekdays (e.g., see the return air trendline for black carbon and UFP, for example). This trend is indicative of cycling of the AHU causing indoor levels of traffic related air pollution to values similar to that exiting the supply (i.e. downstream air cleaning systems).

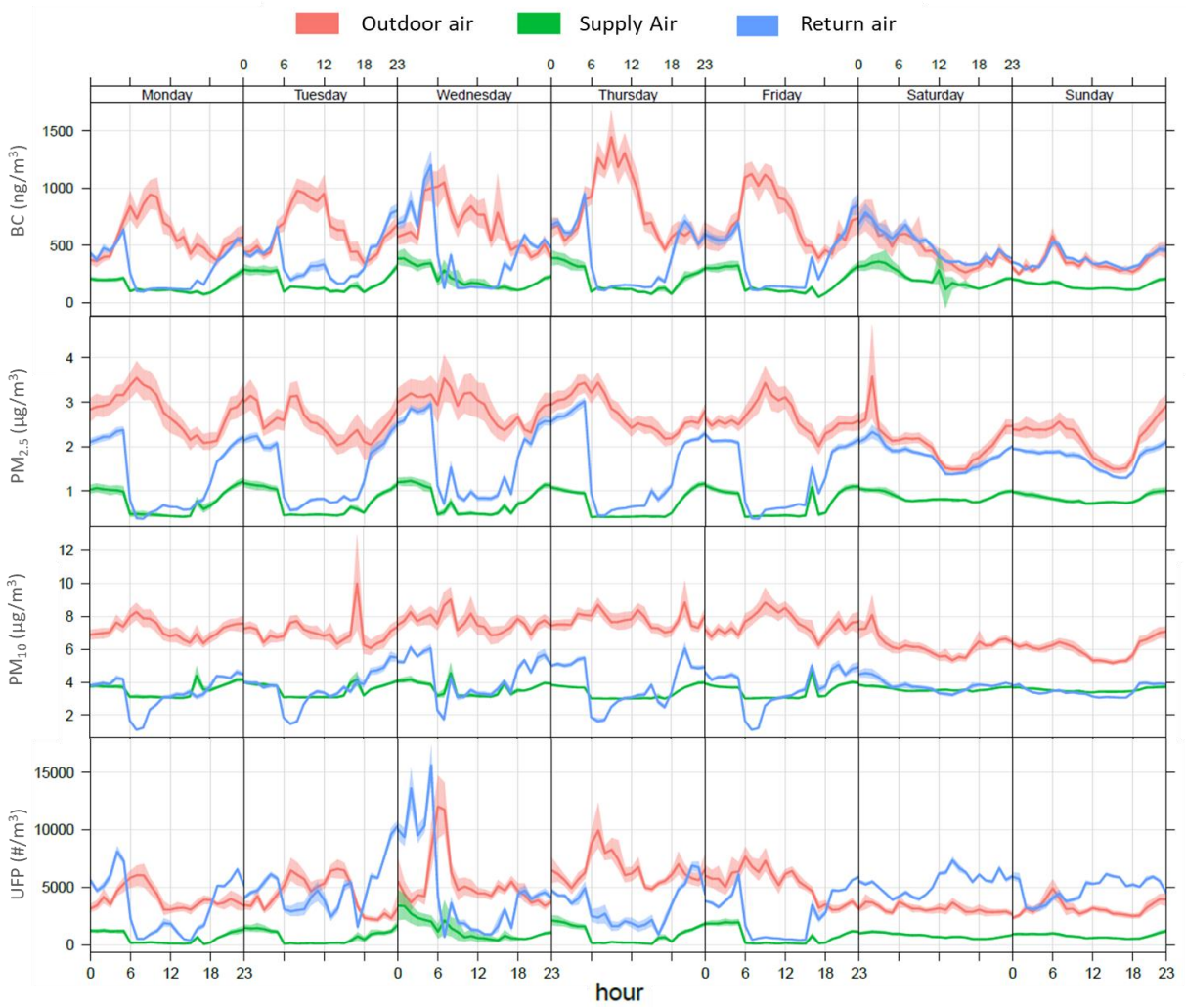

Figure 11. Temporal variation of particle phase pollutants from black carbon (top) to UFP trends (bottom) with outdoor air in red, return (indoor) air in blue and supply (cleaned) air in green.

Figure 11 shows outdoor levels of particles are elevated relative to indoor levels, with concentrations with morning rush hour. Indoor levels track outdoor levels from 6 PM to 6 AM (nighttime) with a clear deviation when the AHU is operating from 6 AM to 6 PM (daytime). Supply air trends are similar to indoor air with lower levels because the measurements are immediately downstream MERV16. We observed a slightly different pattern for PM_{10} due the fact that PM_{10} are not only traffic-related air pollutant as other sources of PM_{10} are pollen, industrial processes, and dust, e.g., a study conducted in Berlin showed that approximately 50% of the urban background PM_{10} was due to long range transport of secondary aerosols and natural sources of particulate matter, with elevations in urban environments due to a combination of exhaust emissions, abrasion processes, and resuspended soil particles (Lenschow et al. 2001).

Figure 12 shows levels of PM at the basketball court and at the HTMS roof (outdoor), measured by purple air sensors. These data show a similar pattern to measurements summarized in Figure 11, with higher magnitudes of PM than indoor levels.

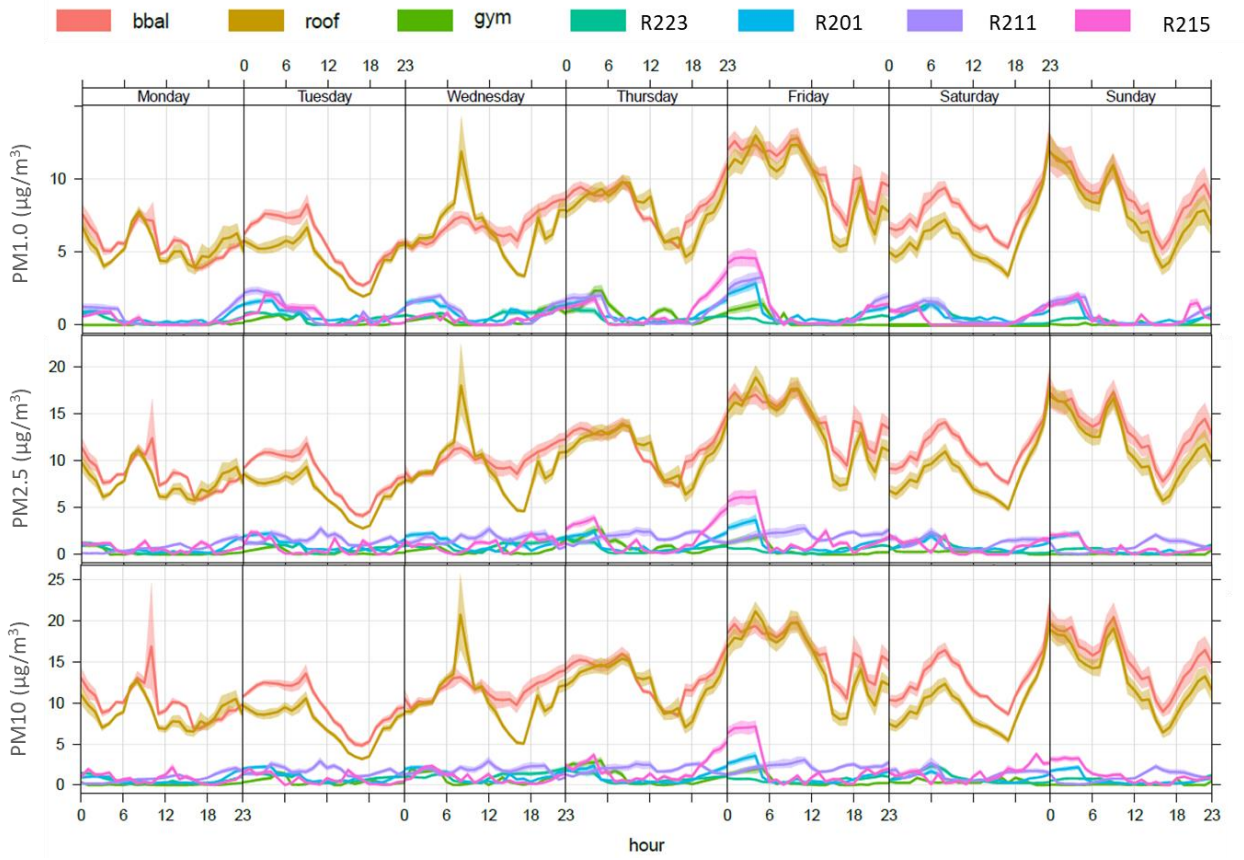

Figure 12. Temporal variation of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} from PurpleAir sensors with R201 in blue, R211 in purple, R215 in pink, R223 in blue-green, gym (gymnasium) in green, roof (penthouse) in yellow, and bbal (basketball field) in red. Note that these trends are from phase II since some sensors were not available during phase III. Phase II levels are slightly higher than phase III levels (section 3.1.1.1.).

As expected, levels in classrooms and the gymnasium are low, especially during school period. Note that the characteristic "U-shape" indicating cycling of AHU (and therefore air cleaning during school periods) is observable in the $PM_{1.0}$ time-series data for all classrooms and the gym.

A similar indoor trend (Figure 13, in blue) was observed for nitrogen dioxide (NO_2), with low levels between 6 AM and 6 PM on weekdays. Figure 13 shows a different pattern for carbon monoxide and nitrogen monoxide as the AHU carbon filters are not designed to remove these two pollutants. One unexpected observation from out data is that it appears there exists a source of CO in the supply air room (AHU-5, Figure 3) when the AHU is not operating (nighttime). We observed consistent nighttime elevations of measured levels of carbon monoxide in the supply air room. However, due to the absence of any combustion sources in the AHU, we do not believe this to be indicative of elevated CO, rather, we suggest that this is likely due to a sampling artifact (i.e., interference) due to the presence of VOCs or particles emitted from the equipment in the AHU. For example, abrasion processes emitted from the fans operating at low speed may emit particles or surfaces/adhesives/lubricants could emit VOCs that scatter/absorb light at the same wavelength at which CO is measured in the infrared spectrum (Plyler, Benedict, and Silverman 1952).

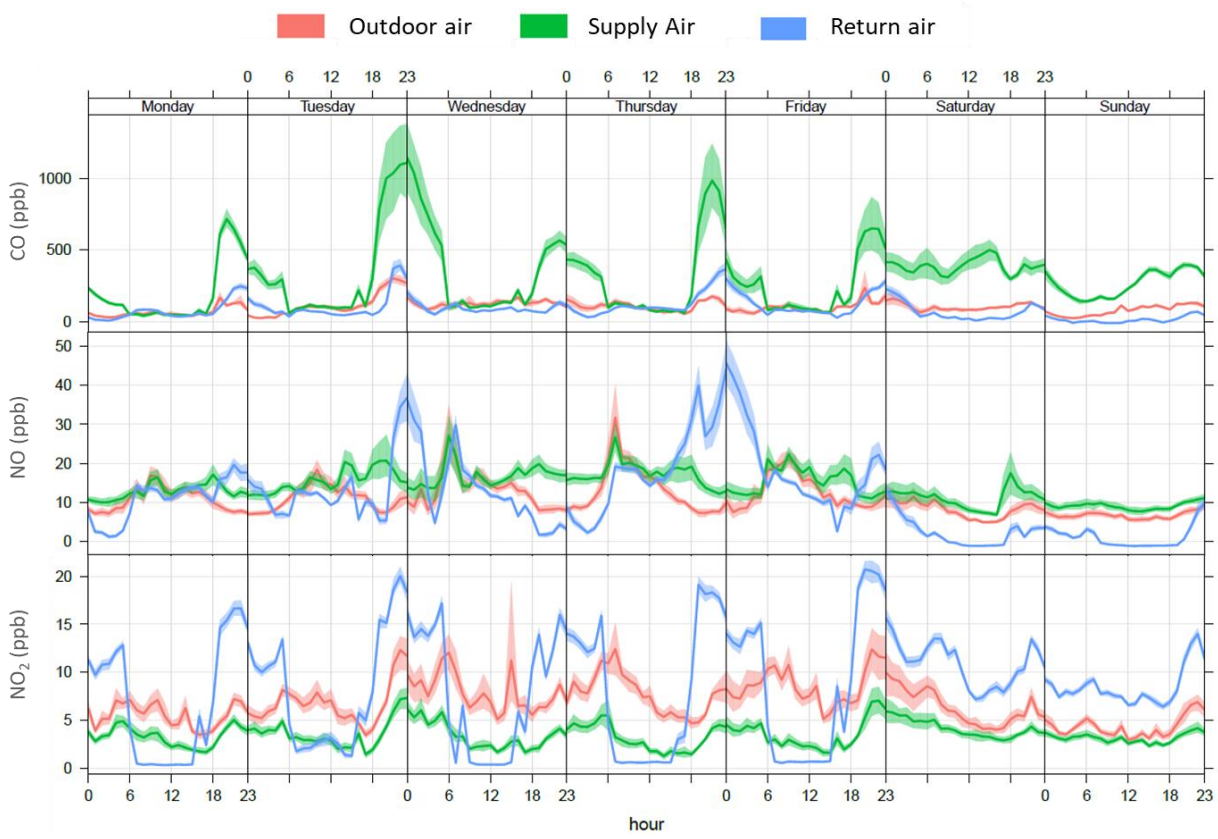

Figure 13. Temporal variation of gas phase pollutants from CO (top) to NO_2 trends (bottom) with outdoor air in red, return (indoor) air in blue and supply (cleaned) air in green.

Temporal variation of VOCs levels such as BTEX were measured by PTR-TOF-MS (Ionicon, PTR-TOF1000) measurements, made in parallel to TD-GC-MS analysis detailed in section 3.1.1.2. VOCs were sampled during phase III only, between May 22th and June 4th continuously (every ten seconds) with a flow rate of 350 mL/min.

Figure 14 shows low benzene levels in general (top plot) and low outdoor levels for all BTEX (red lines in Figure 14). Indoor levels (blue lines) are generally higher than outdoor levels during non-school hours when the AHU is not operating due to a lack of ventilation that create an accumulation due to indoor sources (as aforementioned, e.g., paint, adhesives, solvent use for cleaning, etc). However, during school periods, indoor levels are reduced to levels at or below outdoors due to air cleaning occurring through the activated carbon filters.

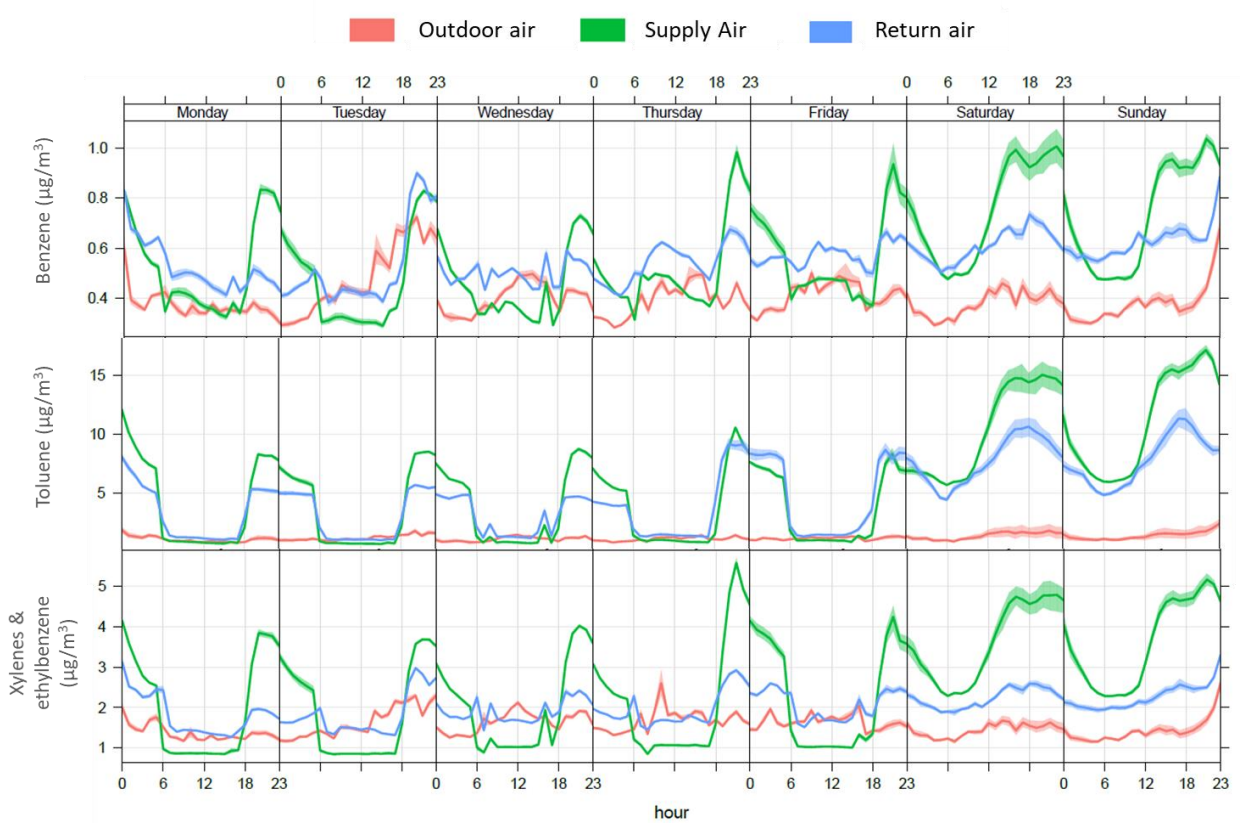

Figure 14. Temporal variation of BTEX from benzene (top) to xylenes & ethylbenzene trends (bottom) with outdoor air in red, return (indoor) air in blue and supply (cleaned) air in green. Note that Xylenes (m-, p-, & o-) and Ethylbenzene cannot be separated with PTR-TOF-MS method while they are with TD-GC-MS method (except m- and p-xylenes).

3.1.4 Trends in outdoor air pollution sources

We have used polar plots to analyze how wind direction influences the level of pollutants (outdoor air). In the following figures (Figures 15 to 17), concentrations of the pollutants are plotted with respect to concentration (color) and the direction the wind is coming from. In addition, the distance away from the center reflects the wind speed. For example, if the pollutant level is low compared to average for the period and the wind is coming from North during that period, it would be plotted with a blueish color on the North side of the center of the plot. A polar plot that is symmetric in color around the center of the plot indicates that the air pollutant comes equally from all directions. When there is asymmetry, it suggests that there is a distinct source coming from a particular direction.

Figure 15 shows a pattern consistent with traffic-related air pollution coming from the freeway (west), especially for short-lived pollutants such as black carbon (BC) and ultrafine particles (UFP). Indeed, wind coming from east has generally lower levels of pollutants.

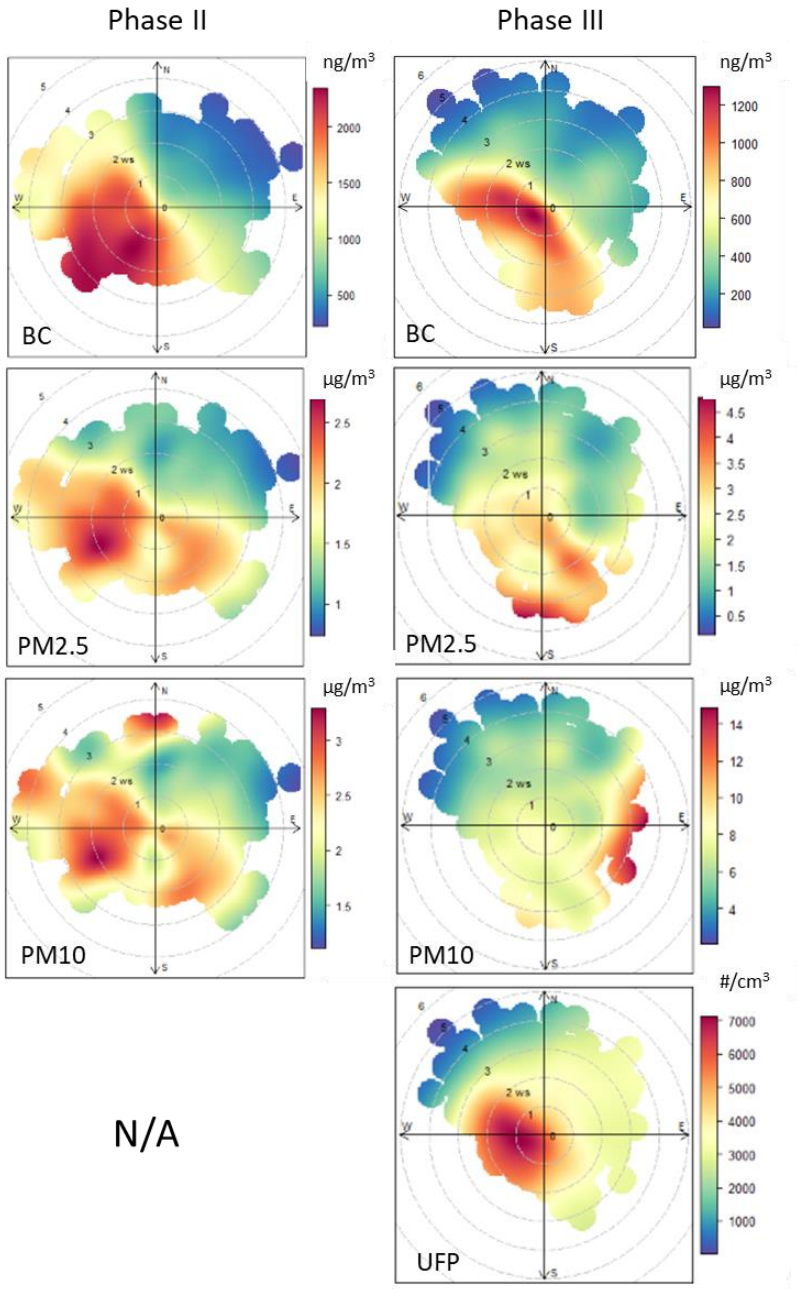

Figure 15. Polar plots of continuous data using meteorological data collected for outdoor air at Harriet Tubman Middle School (particle phase pollutants, from top to bottom: BC in ng/m^3, PM2.5 and PM10 in µg/m^3, and UFP in #/cm^3). Left: data from phase II. Right: data from phase III. Wind speed is in m/s. UFP data from phase II are not available due to instrument issues.

Figure 16 shows a similar trend than figure 15 with higher concentration when the wind is coming from west (phase II and III) and south (phase III) corresponding to the location of the freeway (Figure 1). Wind coming from east has generally lower levels of pollutants.

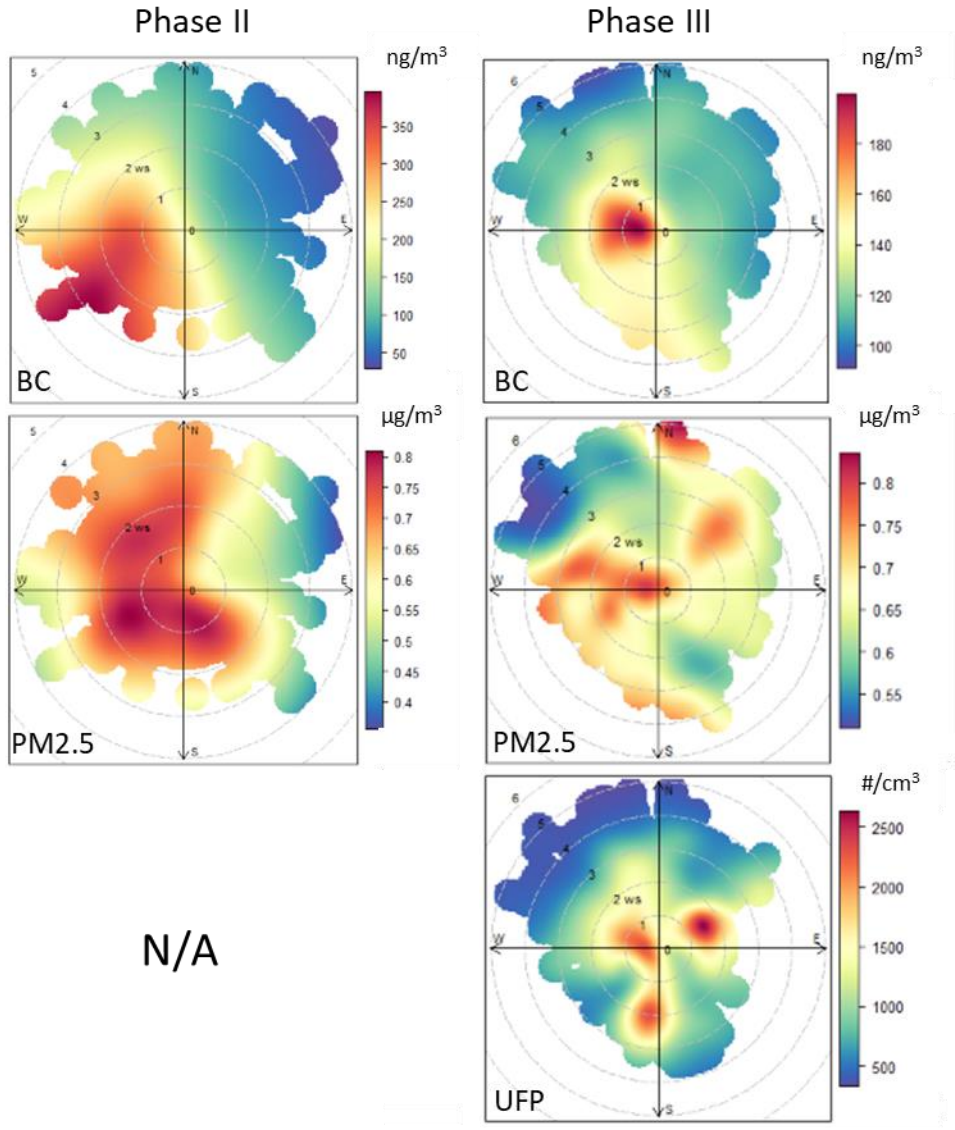

Figure 16. Polar plots of continuous data using meteorological data collected for outdoor air at Harriet Tubman Middle School (gas phase pollutants, from top to bottom: CO, NO and NO_2 in ppb). Left: data from phase II. Right: data from phase III. Wind speed is in m/s.

Figure 17 shows a similar trend than figure 15 with higher concentration when the wind is coming from west (phase II and III) and south (phase III) corresponding to the location of the freeway (Figure 1). Wind coming from east has generally lower levels of pollutants. These polar plots for VOCs are enabled by the high-time resolution measurements made for VOCs via PTR-TOF-MS.

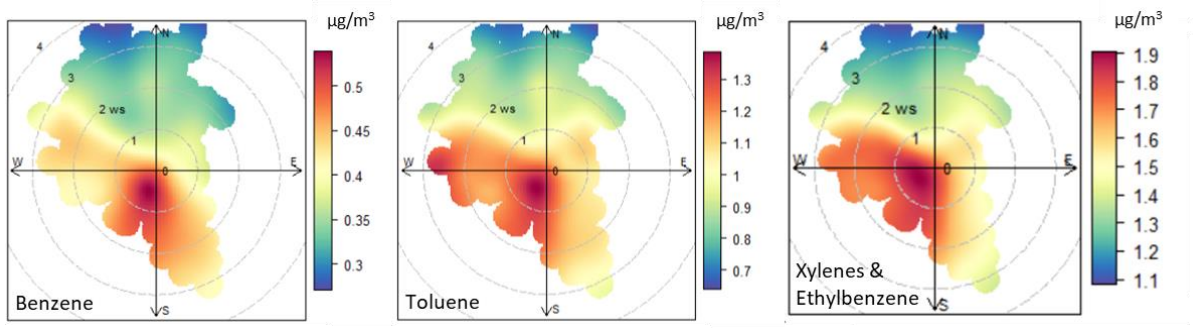

Figure 17. Polar plots of continuous data using meteorological data collected for outdoor air at Harriet Tubman Middle School (BTEX in µg/m^3). Data available only for phase III. Wind speed is in m/s. Consistent with traffic-related air pollutant pattern with higher levels when wind come from west and south.

3.1.5 Comparison with urban background

It is informative to compare the levels at Tubman Middle School to the Oregon Department of Environmental Quality Portland regional N-Core site at SE 55th and Lafayette (SEL). Environmental Protection Agency NCore sites are part of a multi-pollutant network that integrates several advanced measurement systems for particles, pollutant gases and meteorology. The N-Core site is situated to assess the general air quality of the Portland region; thus, comparing outdoor levels at HTMS to this N-Core location enables an assessment of the levels of site air pollution relative to a reasonable surrogate for urban background air pollution levels.

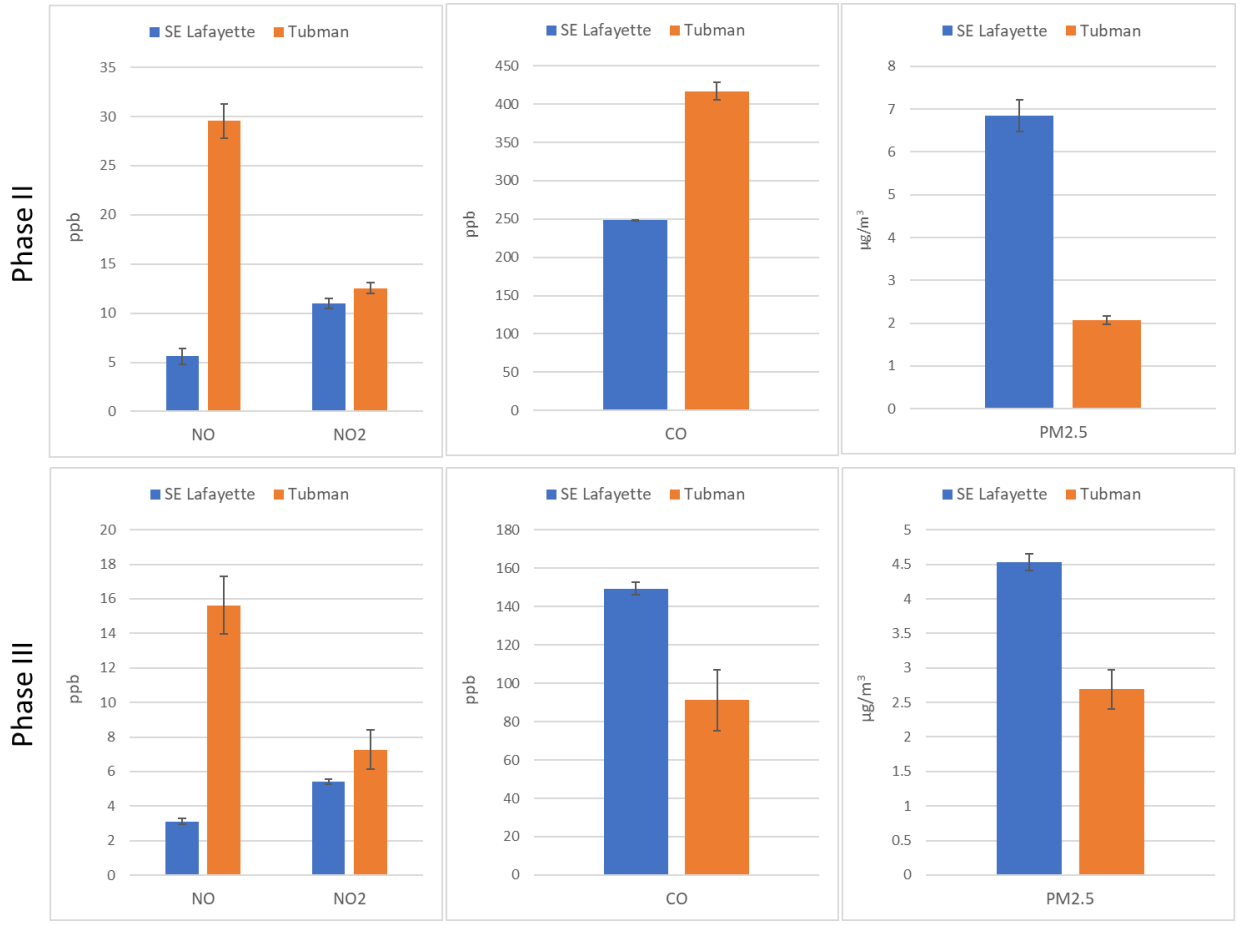

Figure 18. Comparison of Tubman outdoor levels with Portland urban background levels (SE Lafayette) for main traffic-related air pollutants during phase II (top) and phase III (bottom).

During both phase II and III, levels of nitrogen oxides (NO, NO_2) were higher at HTMS than in the Portland urban background (Figure 18). This is expected given the proximity of the site to a prominent source of urban NO and NO_2 (i.e., I-5). However, different trends were observed for carbon monoxide during phase II and III: Tubman level were higher during phase II than Portland urban background while the opposite

was observed during phase III. In both phases, levels were low, and during Phase III were measured to be ~90 ppb, approaching the detection limit of the monitoring device. During both Phase II and Phase III, site levels of $PM_{2.5}$ were below that of urban background measured at SE Lafayette; this is indicative of the fact that on-road mobile sources are not a prominent source of primary $PM_{2.5}$ emissions (Hodan and Barnard 2004).

3.2 Objective 2: Measure spatial variation of air pollutants near HTMS

In order to assess the spatial variation of pollutants around the Tubman site we employed passive nitrogen dioxide samplers and conducted mobile measurements of ultrafine particles and black carbon particles. Nitrogen dioxide sampler surveys were conducted for Phase II (8/29-9/11/18, 9/20-10/2/18,10/7-10/16/19) and Phase III (4/22-5/3/19 and 5/17-29/19) using Ogawa samplers. Representative results are shown in Figure 19. Several features are noteworthy. Higher levels of NO_2 are observed closer to the freeways and decrease as a function of distance from the freeway during both Phases. Higher levels of NO_2 are observed during the fall season of Phase II sampling. This is consistent with meteorological conditions where wind speeds and boundary heights are generally lower. Very low levels are observed from samplers deployed within HTMS during both Phases, reflecting the efficacy of the HVAC air cleaning system in reducing NO_2.

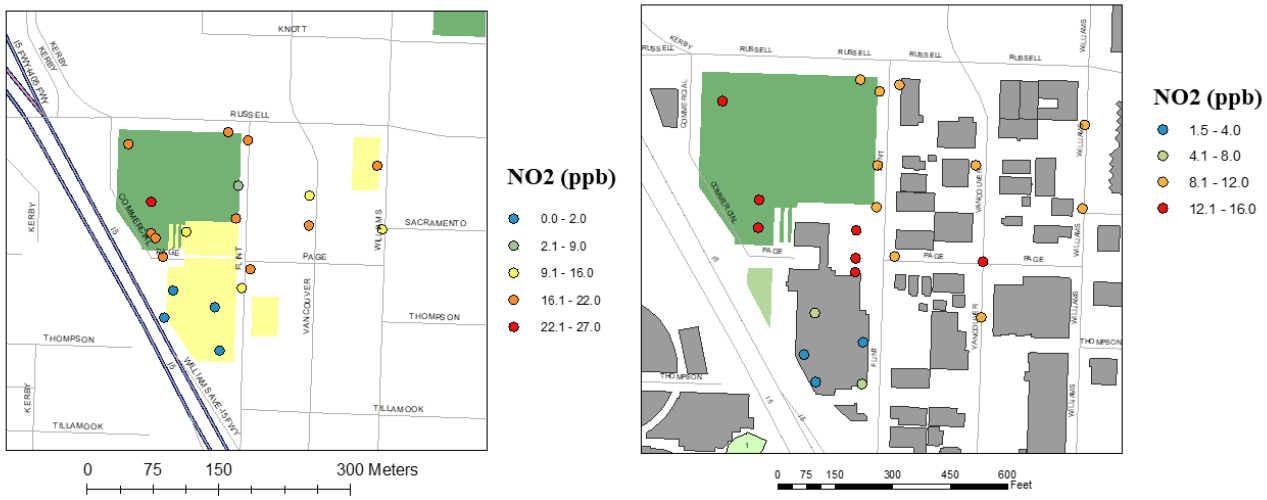

Figure 19. Spatial variation of nitrogen dioxide (in ppb) around Harriet Tubman Middle school during phase II (left) and phase III (right).

We also conducted spatial surveys of ultrafine particles (d<100nm) with a hand-held ultrafine particle sensor (TSI Ptrak) as well as black carbon particles with a micro-aethalometer (AethLabs, MA300) during phase III. A PSU conducted surveys traversing the HTMS schoolyard and its environs during periods in which students were observed to be outside for entrance, recess, lunch, dismissal. The periods sampled were: 8-10AM, 9-10AM, 11:15 AM -12:45 PM, 1-2PM, 3:45-4:15PM, 4:30-5PM (10/15/18, 4/26, 5/5, 5/16 and 5/22/19). Data from each of the instruments were averaged during these periods and represented in Figures 20 and 21. For UFP, the pattern is similar to NO_2. Higher levels are observed near the freeway, especially during Phase II fall season. During Phase III, we observed significantly higher levels on 5/16/19

when wind speeds were lower and southerly (in contrast to northwesterly winds on the other sampling days).

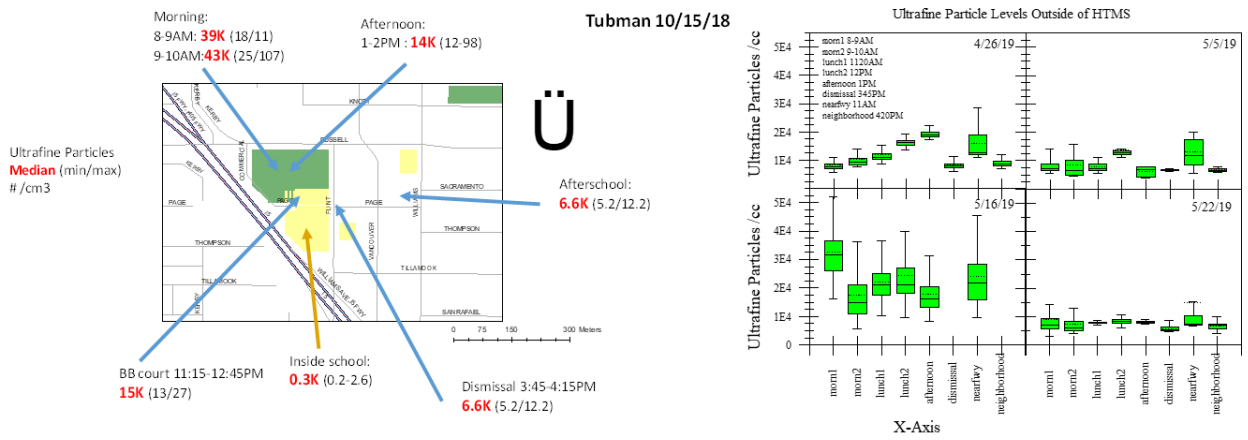

Figure 20. Spatial variation of ultrafine particles (in #/cm^3) around Harriet Tubman Middle school during phase II (left) and phase III (right).

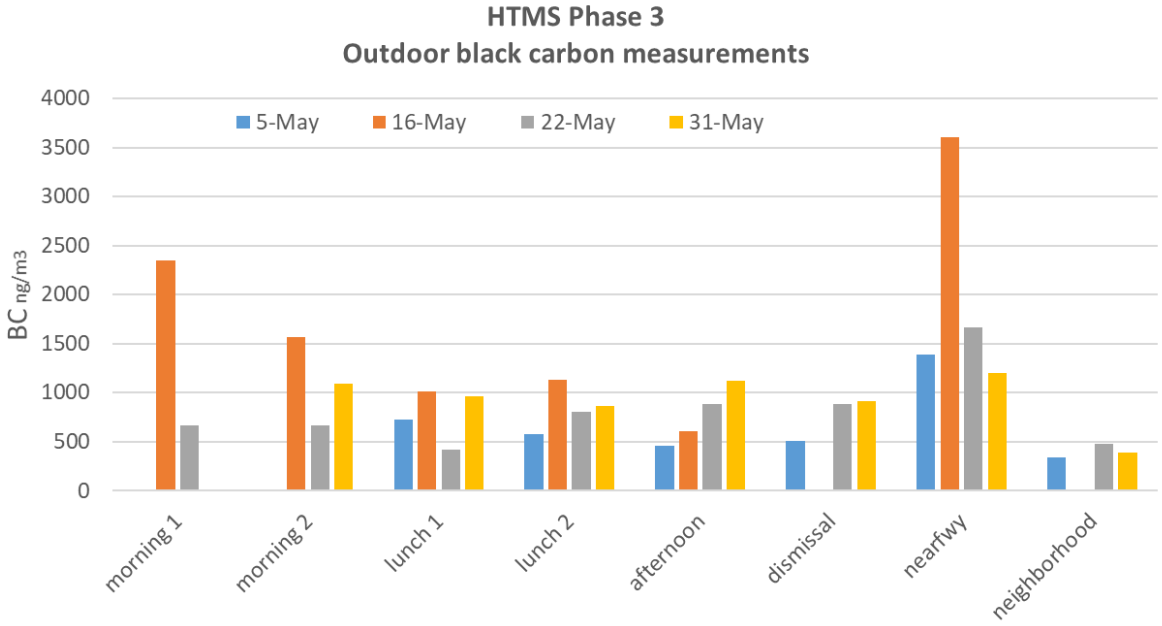

Figure 21. Spatial and temporal variation of black carbon (in ng/m^3) around Harriet Tubman Middle school during phase III.

Higher levels of black carbon particles are also observed on 5/16. The black carbon measurements clearly show elevated levels near the school compared to the neighborhood background (< 500 ng/m3).

Outdoor monitoring during Phase II and III around HTMS demonstrates that outdoor areas where students are active are impacted by TRAP pollutants at levels significantly above neighborhood background levels.

3.3 Objective 3: Evaluate air pollution removal efficiency of air treatment systems

During the renovation of Harriet Tubman Middle School and prior to initiation of Phase II air monitoring, PPS installed an air cleaning system consisting of (in order of installation in the direction of airflow): MERV 8 filter bank, MERV16 filter bank, activated carbon filter bank (Camfil, LGX048 media), final MERV8 filter bank. The removal efficiency of the AHU has been evaluated through the first nine months of operation by measurements made during Phase II and Phase III monitoring. Note that with the exception of black carbon, estimates of removal efficiency made in Phase III are derived from direct measurements made by sensors placed immediately upstream and downstream relevant unit operations. For particle phase removal efficiency measurements, real-time particle counters (TSI, Optical Particle Sizer and TSI, Nanoscan SMPS) were placed upstream and downstream all air cleaning systems and thus include the activated carbon canisters. For gas-phase removal efficiency measurements, measurements of volatile organic compounds and nitrogen dioxide were made by placing measurements immediately upstream and downstream the activated carbon filters. For black carbon measurements, estimates of removal efficiency of black carbon are made by estimating the upstream concentration of BC ahead of the particle filter by estimating the percentage of outdoor air mixed into return air using air temperature measurements. Table 5 shows the results of the measurements and calculations of particle removal efficiency of the particle air cleaning systems.

Table 5. Summary of removal efficiency for particle phase compounds.

Compound	Theoretical removal[#]	Phase II (Sept-2018)	Phase III (June 2019)
Black carbon	Not available	93% removal*	79% removal*
$PM_{2.5}$	>95%	90% removal	81% removal
PM_{10}	>95%	80% removal	54% removal
Coarse particles**	>95%	n/d	46% removal
Ultrafine particles	>98%	98% removal	96% removal

[#] theoretical removal estimates are calculated using equations from Azimi et al. (2014) for a MERV8 and MERV16 filter (in series).

* average removal calculated with estimates of mixed air levels. Mixed air levels were estimated from measured outdoor and return air levels, weighted by outdoor air fraction. Outdoor air fraction is calculated from measurements of air temperatures made in outdoor air, return air, and mixed air. Presence of fans, surfaces introduce error to this calculation.

** coarse particles: particle with diameter between 2.5 µm and 10 µm.

Over the course of the academic year (i.e., from Phase II to Phase III), measured removal efficiencies of particles decreased for all classes of particles. Reductions in removal efficiencies were most pronounced for larger particles (PM_{10}) and were less substantial for smaller particles ($PM_{2.5}$ and ultrafine particles). However, in Phase III, we calculated removal efficiency for only coarse particles, and determined that 46% removal of coarse particles is achieved by the air cleaning system. We believe this reflects a source of coarse particles in the supply air, rather than the filter removal efficiency deviating so substantially from theoretical removal for only the coarse particle size range. Possible sources of coarse particles include abrasion processes in fans, or fans operating to push air into the building are resuspending coarse mode particles that settle in the supply room during periods of inoperation or system idling.

In theory, particle removal efficiency in flow across a filter should not decrease with time; as the filter loads, the removal efficiency should be maintained or possibly increase due to reduction of porosity of the filter. However, accompanying loading of the filter is an increase in pressure drop across the filter (again, due to loaded particle mass reducing filter bulk porosity, creating a more resistive flow path for air). We speculate that an increase in pressure drop across the filter may underlie the observed reduction in particle removal efficiency via induced bypass of a greater portion of airflow around the filter (e.g., the resistance of air moving through the seal between the filter and the filter housing may become more similar to that of air moving through the filter). **We recommend that PPS discuss with the lead contractor who constructed the air handling unit regarding trending of pressure drop and/or flows across this bank of filters. If the AHU cannot report this information, it is recommended that the AHU be instrumented to record these important data to inform filter change out schedule and filter removal efficiency measurement.**

Table 6 and Figure 22 are the removal efficiencies for gas-phase air pollutants of concern. Removal efficiencies were monitored from September 2018 through June 2019, and show variation in trends of removal efficiency across the compounds (Figure 22). Initially, removal of all compounds with the exception of benzene and toluene were high (>80%). Removal efficiency of nitrogen dioxide and styrene are observed to decrease over the monitoring period while benzene and toluene were observed to increase. Other compounds had consistently high removal efficiencies or experienced temporary reductions in removal efficiency during the winter months.

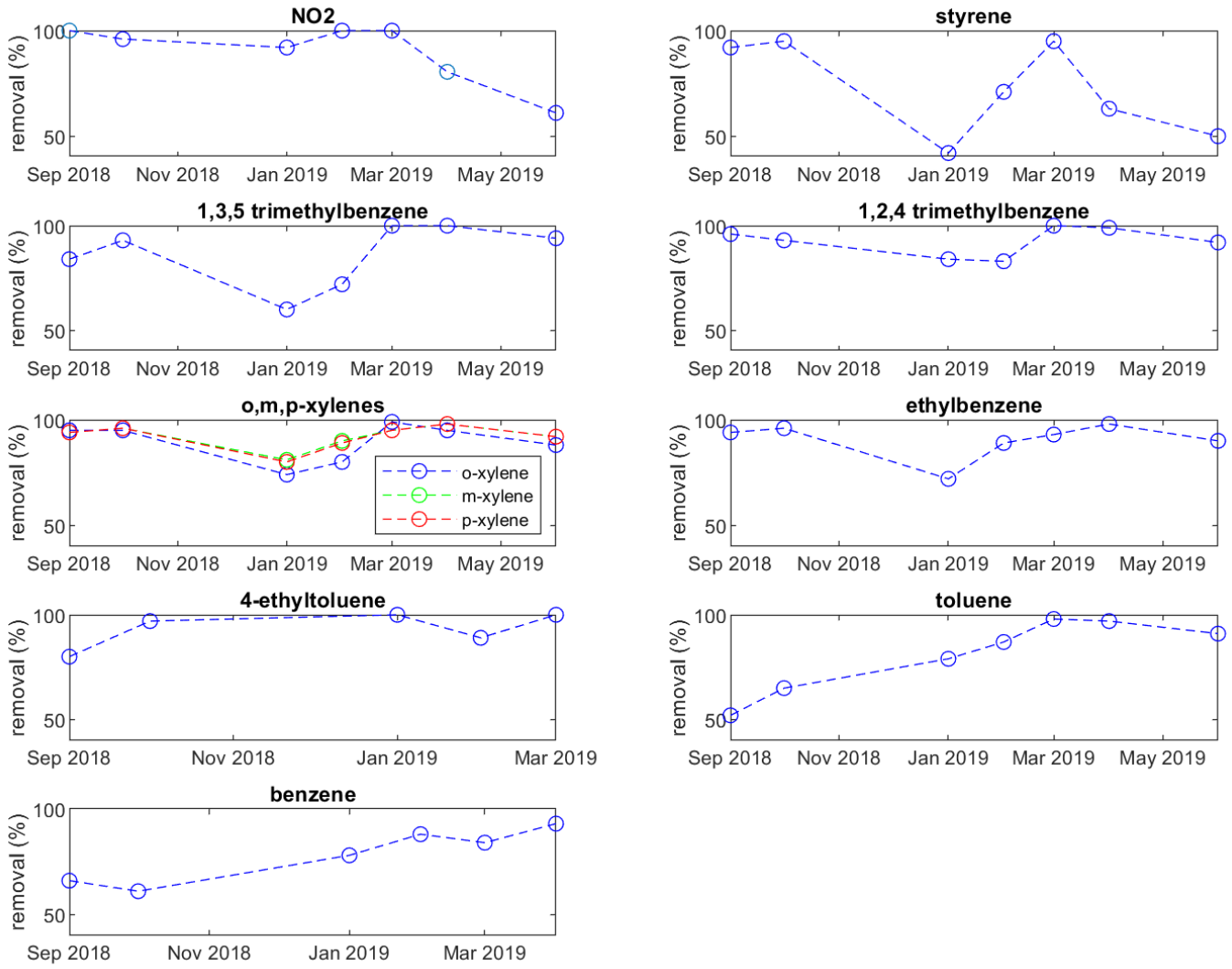

Figure 22. Summary of time-series measurements of removal of selected gas-phase air pollutants of concern.

Based on our measurements of removal efficiency of particle and gas phase air pollutants at Harriet Tubman Middle Schools, **we recommend that PPS continue to monitor particle, VOC and NO_2 removal efficiency across the particle and carbon filters on at least a quarterly basis to ensure change out of the particle and activated carbon filters are performed at an appropriate time.**

Table 6. Summary of the removal efficiency (%) for selected gas phase compounds associated with traffic related air pollution. Dates refer to the date of measured removal across the activated carbon filter.

Compound	Advertised removal*	Sept. 2018	Oct. 2018	Jan. 2019	Feb. 2019	Mar. 2019	Apr. 2019	Jun. 2019	Uncertainty**
NO_2	98%	N.A.	96%	92%	99%	>99%	N.A.	61%	
styrene	>99%	92%	95%	42%	71%	95%	63%	50%	65%
1,3,5-trimethylbenzene	>99%	84%	93%	60%	72%	100%	100%	94%	29%
1,2,4-trimethylbenzene	>99%	96%	93%	84%	83%	100%	99%	92%	9%
o-xylene	>99%	95%	95%	74%	80%	99%	95%	88%	14%
p-, m-xylenes	>99%	94%	96%	81%	90%	95%	98%	92%	10%
ethylbenzene	>99%	94%	96%	72%	89%	93%	98%	90%	7%
4-ethyltoluene	>99%	80%	97%	100%	89%	100%	N.A.	N.A.	47%
toluene	>99%	52%	65%	79%	87%	98%	97%	91%	10%
benzene	>99%	66%	61%	78%	88%	84%	93%	N.A.	67%
acetone	80%	N.A.	83%	72%	86%	N.A.	100%	100%	9%

*Advertised removal is the removal efficiency stated by the manufacturer (Camfil) as a function of specific flow rate in the AHU, contact time and concentration of pollutant.

**average uncertainty calculated across the time-series 7 measurements (2 replicates for each measurement upstream and downstream the filters). Note that the concentration downstream are close to or under the method detection limit, in some cases increasing uncertainty

3.4 Objective 4: Evaluate potential for infiltration of traffic-related air pollutants across the building envelope

We used polar plots to assess the potential for infiltration of outdoor air across the building envelope to act as a source of traffic related air pollutants to the indoor environment. This approach is similar to the approach used in Section 3.1.4, however, instead of overlaying outdoor air pollution levels with site meteorology, we use indoor air (return air) levels. Similar to the analysis of section 3.1.4, observation of persistently elevated return air levels of traffic-related air pollutants with certain outdoor meteorological conditions (i.e. a combination of wind direction and wind speed) would be indicative of infiltration of outdoor air into the building.

Figure 23 shows polar plots for return air levels of particle-phase TRAP during phase II and III for the school period. Generally, low levels of TRAP in indoor air were observed. However, the highest concentrations of indoor black carbon (an air pollutant that also serves as a proxy for TRAP) were observed when the wind is coming from the freeway direction (west and south). Contrasting the black carbon polar plot from phase II to phase III shows that lower indoor BC levels were observed and there existed a generally weaker trend with winds from the south and southwest during phase III. This is possible a result of ongoing renovations to the school during Phase II on the I-5 facing side of the building. In contrast with black carbon, $PM_{2.5}$ shows more diffuse trends, with elevated indoor PM levels occurring with a broader range of outdoor wind conditions; this is consistent with expectations as $PM_{2.5}$ is a regional air pollutant with contributions from a more diverse range of sources than black carbon.

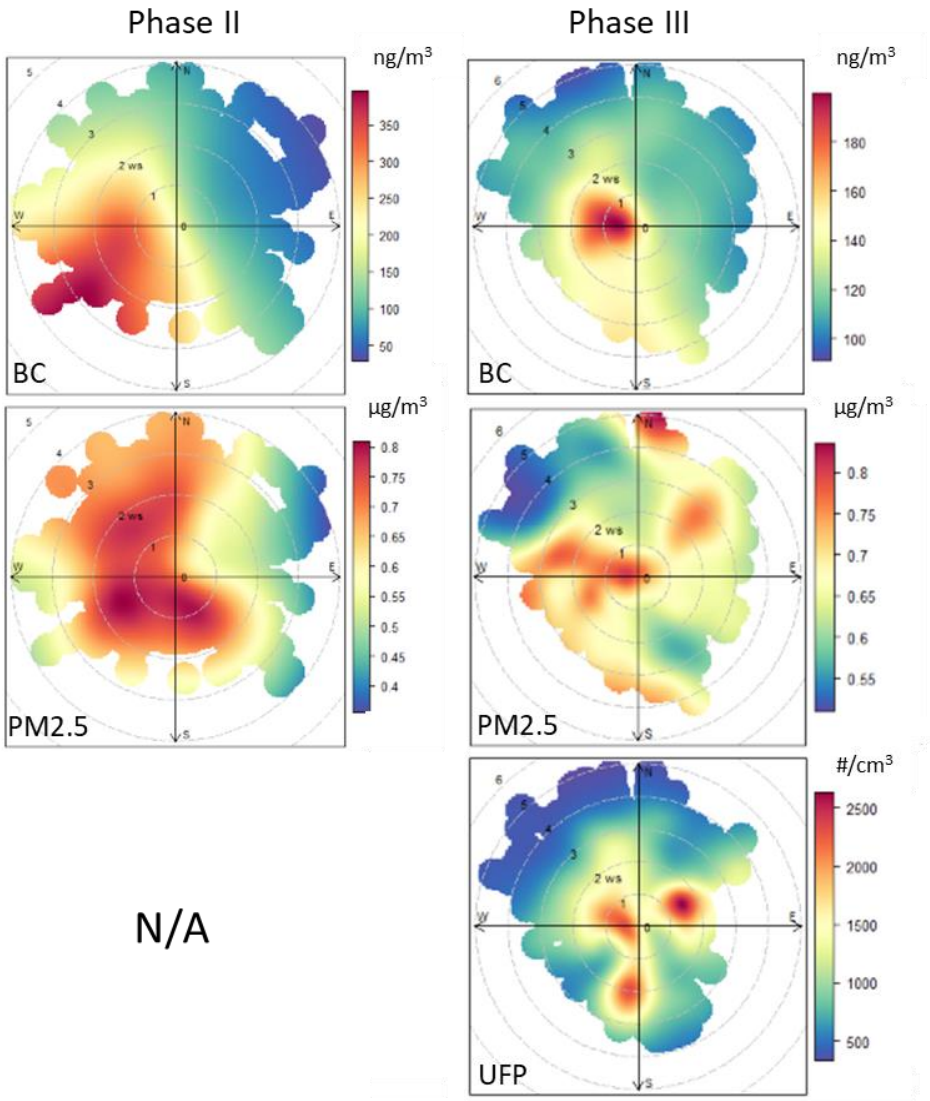

Figure 23. Polar plots of continuous data using meteorological data collected for indoor air (return air) at Harriet Tubman Middle School for the school period (particle phase pollutants, from top to bottom: BC in ng/m^3, $PM_{2.5}$ and PM_{10} in µg/m^3, and UFP in #/cm^3). Left: data from phase II. Right: data from phase III. Wind speed is in m/s. UFP data from phase II are not available due to instrument issues.

Figure 24 shows polar plots for return air levels of gas-phase TRAP during phase II and III. Similar to the results shown in Figure 18, Figure 19 shows that during phase II, there may have existed infiltration of CO and NO during Phase II, while associations of these compounds in indoor air with meteorological conditions are less evident in Phase III. Again, we attribute this difference from Phase II to Phase III to be likely the result of the completion of a renovation work to the envelope following phase II.

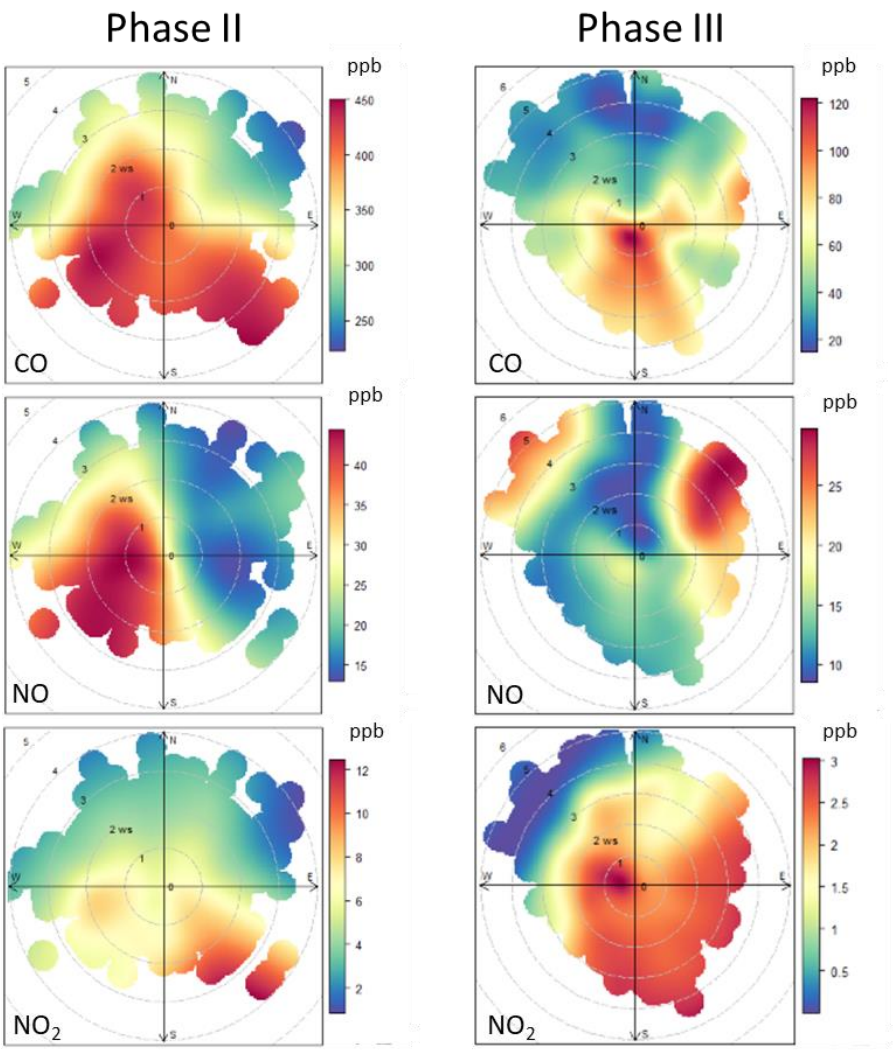

Figure 24. Polar plots of continuous data using meteorological data collected for indoor air (return air) at Harriet Tubman Middle School (gas phase pollutants, from top to bottom: CO, NO and NO_2 in ppb). Left: data from phase II. Right: data from phase III. Wind speed is in m/s.

Note that this analysis should be considered only generally informative, as the mean residence time of indoor air in the school is currently unknown**. We recommend that PPS confer with the mechanical contractor to determine design values of supply, return, and outdoor air flowrate to enable estimates of residence time of air in the school.** Prior conversations with the mechanical contractor indicate that air flows through the air handling unit can be recorded by installed monitoring systems in the existing AHU. **If available, these data could be used to more accurately identify potential locations of infiltration in the building envelope by enabling time-correction of measurements of return air pollutant levels to account for the residence time in the building when associating with outdoor meteorological conditions.**

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5 Appendices

5.1 Additional analysis

5.1.1 Analysis of VOCs other than BTEX

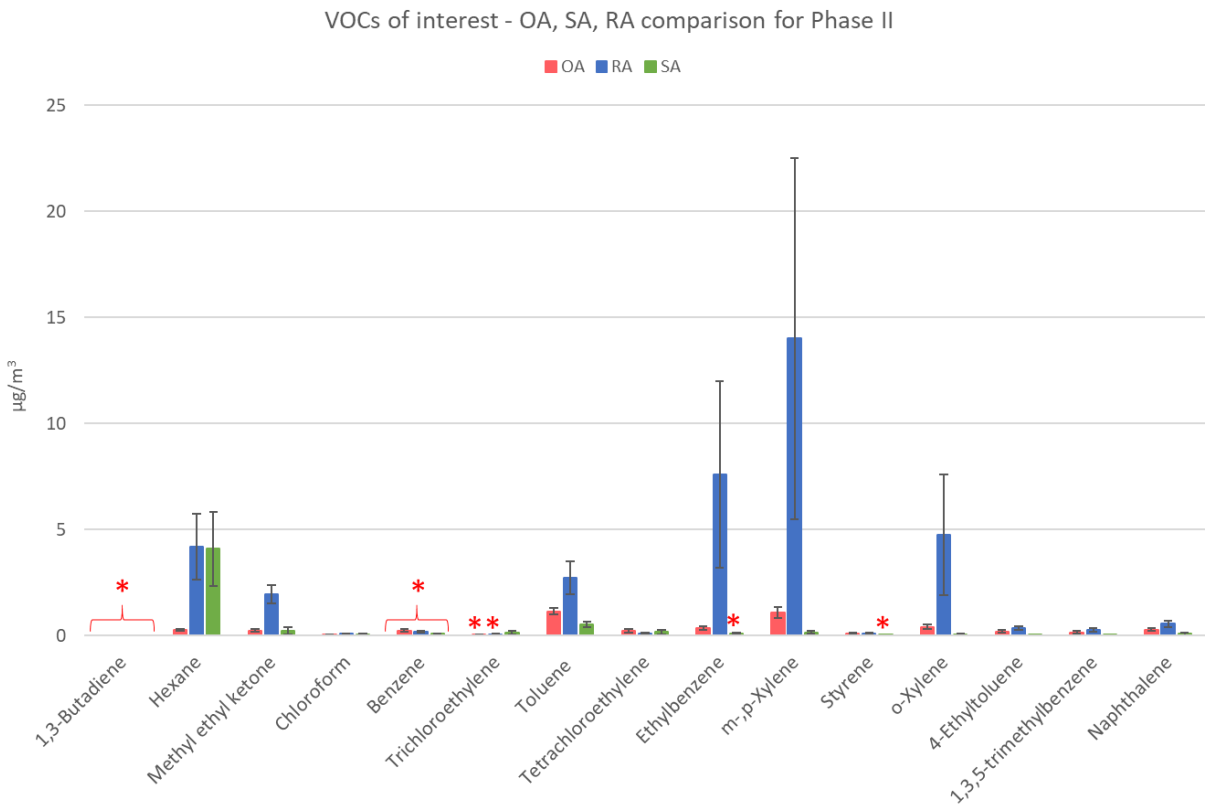

Figure A1. Concentration in µg/m^3 of several Volatile Organic Compounds of interest (potentially harmful) for phase II. Red star (*) means that the levels are under the method detection limit.

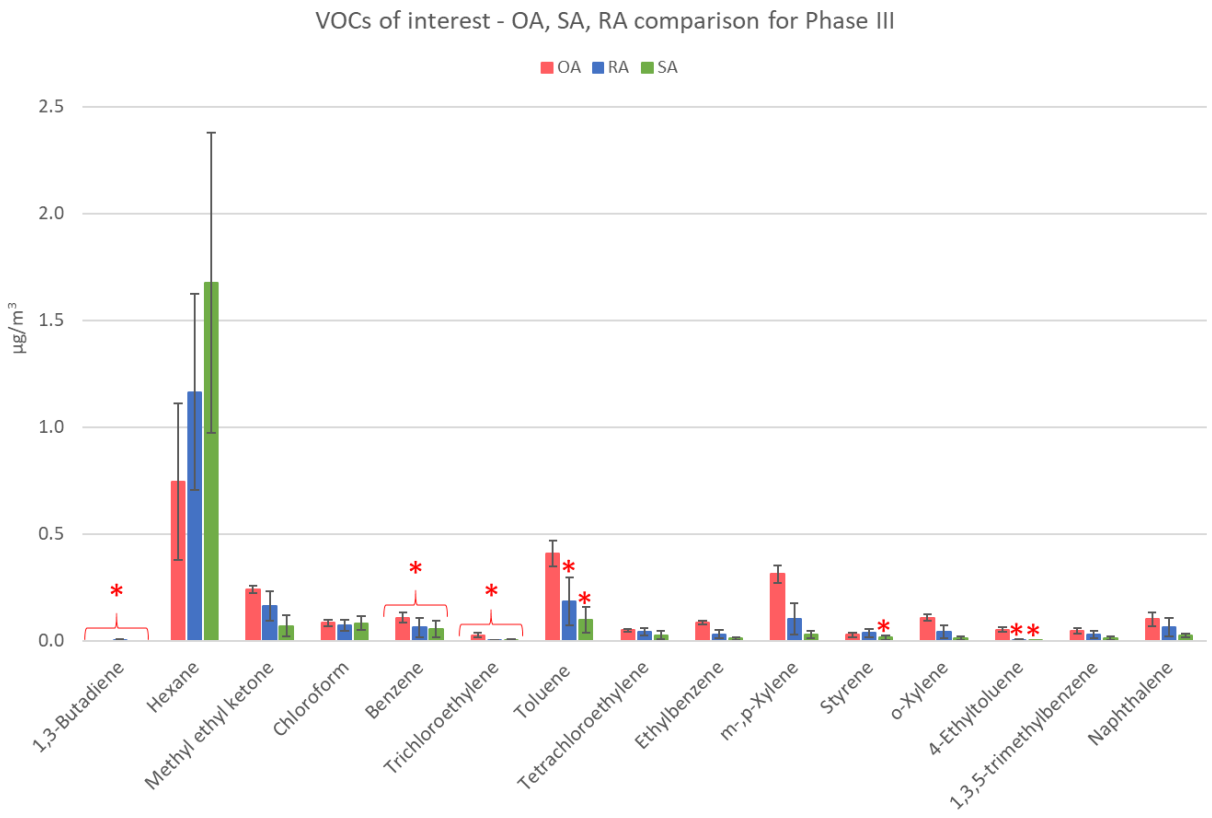

Figure A2. Concentration in µg/m^3 of several Volatile Organic Compounds of interest (potentially harmful) for phase III. Red star (*) means that the levels are under the method detection limit.

5.1.2 Exposure concentration of traffic-related air pollutant at HTMS

Table A1. Summary of exposure concentration of particle phase traffic-related air pollutants at HTMS during Phase III. Data sent to William Lambert, PhD for health risk assessment.

	PM2.5_OA ($\mu g/m^3$)	PM2.5_SA ($\mu g/m^3$)	PM2.5_RA ($\mu g/m^3$)	PM10_OA ($\mu g/m^3$)	PM10_SA ($\mu g/m^3$)	PM10_RA ($\mu g/m^3$)	UFP_OA ($\#/cm^3$)	UFP_SA ($\#/cm^3$)	UFP_RA ($\#/cm^3$)	BC_OA (ng/m^3)	BC_SA (ng/m^3)	BC_RA (ng/m^3)
min	0.36	0.36	0.31	2.94	2.93	0.99	89	26	333	0	0	12
5%tile	0.38	0.37	0.35	2.96	2.95	1.09	1042	59	384	41	0	77
25%tile	1.25	0.38	0.52	5.28	2.96	2.17	2948	97	465	290	62	107
mean	2.69	0.45	0.71	7.39	3.08	3.15	5282	265	1712	829	117	158
median	2.36	0.41	0.62	7.12	2.99	2.96	4513	149	547	615	103	130
75%tile	3.85	0.44	0.74	9.33	3.03	3.87	6801	225	1003	1127	151	156
95%tile	5.95	0.58	1.47	13.12	3.43	5.99	11951	466	8453	2325	256	225
max	12.44	3.57	4.75	55.54	11.45	13.69	63838	19736	33371	17858	3918	2748

Table A2. Summary of exposure concentration of gas phase traffic-related air pollutants at HTMS during Phase III an. Data sent to William Lambert, PhD for health risk assessment.

	CO_OA (ppb)	CO_SA (ppb)	CO_RA (ppb)	NO2_OA (ppb)	NO2_SA (ppb)	NO2_RA (ppb)
min	0.00	0.00	0.00	0.56	0.00	0.00
5%tile	0.00	0.00	0.00	1.75	0.49	0.00
25%tile	24.82	31.63	19.49	3.45	1.11	0.54
mean	91.16	90.83	73.87	7.26	2.82	0.88
median	83.87	88.52	70.19	5.75	2.03	0.65
75%tile	140.84	136.06	117.08	9.64	3.83	0.75
95%tile	235.73	224.08	213.24	17.19	7.58	2.62
max	2244.04	1130.41	428.66	230.99	26.45	28.32

Table A3. Summary of exposure concentration of volatile organic compounds at HTMS during Phase III . Data sent to William Lambert, PhD, for health risk assessment.

	Benzene_OA (µg/m^3)	Benzene_RA (µg/m^3)	Benzene_SA (µg/m^3)	Toluene_OA (µg/m^3)	Toluene_RA (µg/m^3)	Toluene_SA (µg/m^3)	Ethylbenzene_OA (µg/m^3)	Ethylbenzene_RA (µg/m^3)	Ethylbenzene_SA (µg/m^3)
min	0.05	0.00	0.00	0.26	0.02	0.00	0.06	0.00	0.00
max	0.18	0.20	0.17	0.56	0.55	0.29	0.11	0.10	0.03
5%tile	0.06	0.00	0.00	0.27	0.02	0.01	0.06	0.00	0.00
25%tile	0.09	0.00	0.00	0.31	0.03	0.03	0.07	0.00	0.00
75%tile	0.12	0.11	0.10	0.49	0.27	0.14	0.10	0.03	0.01
95%tile	0.16	0.18	0.16	0.55	0.49	0.26	0.11	0.09	0.02
mean	0.11	0.06	0.05	0.41	0.18	0.10	0.08	0.03	0.01
median	0.10	0.00	0.00	0.41	0.05	0.03	0.08	0.01	0.00

	m-,p-Xylene_OA (µg/m^3)	m-,p-Xylene_RA (µg/m^3)	m-,p-Xylene_SA (µg/m^3)	o-Xylene_OA (µg/m^3)	o-Xylene_RA (µg/m^3)	o-Xylene_SA (µg/m^3)
min	0.21	0.01	0.00	0.07	0.01	0.00
max	0.42	0.37	0.09	0.14	0.14	0.04
5%tile	0.22	0.01	0.00	0.07	0.01	0.00
25%tile	0.25	0.02	0.01	0.08	0.01	0.00
75%tile	0.36	0.09	0.03	0.12	0.04	0.01
95%tile	0.41	0.31	0.08	0.14	0.12	0.03
mean	0.31	0.10	0.03	0.11	0.04	0.01
median	0.32	0.03	0.01	0.12	0.01	0.01

5.2 Quality assurance and quality control

The QA/QC practices employed in the project are consistent with methods used for peer-reviewed atmospheric research projects. Our measurements are not intended to assess regulatory compliance (this is the role of Oregon DEQ). The QA/QC measures employed are summarized in Table A-1.

We calibrated instruments with standard gases and methods and/or relied on recent factory calibrations. Due to the nature of the site, a school under construction, we did not consider it feasible or wise to use on-site calibration with compressed toxic gases.

Table A4. Summary of quality assurance and quality control measures.

Parameters Monitored	Instrument Manufacturer/Make	QA/QC employed
Nitrogen oxide, nitrogen dioxide	Teledyne T200P Teledyne T200UP	Ecotech 1100 Calibrator, EPA Protocol Gas Calibration before deployment Return to lab monthly for recal.
Carbon monoxide	Ecotech Serinus 30	Factory calibration Calibration before deployment Return to lab monthly for recal.
Black Carbon	Magee Scientific AE33	Factory calibration Calibration before deployment Return to lab monthly for recal.
PM 2.5 continuous	PurpleAir sensors	Internal duplicate measurements
SMPS/OPS	TSI 3910 NanoScan, TSI 3330 OPS	Factory calibration, yearly re-certification
UFP mobile transects	TSI PTrak	Factory calibration
Nitrogen dioxide passive samples	Ogawa samplers	Laboratory calibration
Volatile Organic Compounds continuous	PTR-MS	AirGas certified standard or EPA TO-15 calibration standard Monthly calibration
Volatile Organic Compounds	Grab samples	AirGas certified standard or EPA TO-15 calibration standard Monthly calibration

A Method Detection Limit (MDL) and an analytical precision* was calculated for each volatile organic compound monitored following EPA compendium method TO-17 and the results are given in table A2. *Analytical precision is defined as the extent to which results agree with one another.

Table A5. Summary of MDL and analytical precision for each VOCs of interest.

Compounds	Method detection limit (µg/m³)	Analytical precision (% of reading) #
Benzene	4.863	8
1,3-butadiene	0.092	N.A.
Chloroform	0.014	15
Hexane	0.029	18
Naphthalene	0.012	32*
Tetrachloroethylene	0.248	50*
Toluene	0.298	15
Trichloroethylene	0.133	2
m- & p-xylenes	0.006	3
o-xylene	0.003	2
Styrene	0.028	30*
Ethylbenzene	0.004	11
1,3,5-trimethylbenzene	0.001	9
Ethyltoluene	0.019	N.A.
Methyl ethyl ketone	0.024	19

*does not meet the expected performance criteria of Compendium Method TO-17/TO-15 (within 20% of reading). The results obtained for these compounds are not precise enough.

#Values are calculated from measurements made upstream of carbon filter only. Downstream concentrations are generally close to or under the method detection limit, since the carbon filter is removing organic compounds.