

Indoor and outdoor air quality at Harriet Tubman Middle School and the design of mitigation measures: Phase I 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 in Portland, OR. Portland State University has completed Phase I of the proposed project (start date February 1, 2018), which included: 1.) Deployment of an air quality monitoring campaign at the school site; 2.) Recommendations regarding the design of the building heating, ventilation and air-conditioning (HVAC) system and building renovation; and 3.) Initiation of site model development for wind-tunnel tests to characterize site airflows and evaluate possible outdoor air quality mitigation strategies.

This report serves to summarize the findings and progress to date of this Phase I effort as well as recommendations generated from the Phase I effort.

Key findings and progress:

Outdoor air monitoring:

Finding #1: There is a gradient of traffic related pollutants that decreases as function of distance away from I-5 N, reaching background levels about 200-300 feet from the freeway.

Primary evidence:

- Passive sampling of nitrogen dioxide in a ~0.1 km² area around Tubman Middle School (§3.4)
- Mobile transects of ultrafine particles around Tubman Middle and Lillis Albina City Park (§3.4)

Finding #2: Air sampled on the SW side (freeway side) of Tubman Middle School is heavily impacted by freeway emissions. Air sampled on the Flint Ave. side is also impacted by freeway emissions but pollution is at a lower concentration.

Primary evidence:

- Measurements from freeway have elevated levels of black carbon, carbon monoxide, ultrafine particles and nitrogen oxides (§3.3.1-2)
- Diurnal patterns consistent with traffic patterns (§3.3.1-2)
- Simultaneous measurements of tracers (NO₂, BC) on I-5 and Flint Ave. sides of building (§3.6)

Finding #3: Many air pollutants measured at Tubman are elevated compared to Portland urban background site (DEQ SE Lafayette). However, criteria pollutants are below National Ambient Air Quality Standard for the monitoring period. Toxic metals were below Oregon Ambient Benchmark Concentrations (except for arsenic). Some toxic volatile organic compounds were above Ambient Benchmark Concentrations.

Primary evidence:

- Comparison of monitored data with ODEQ urban monitoring site for NAAQS (§3.5, §3.7.3)
- Comparison of monitored data with ODEQ Humboldt site for VOCs (§3.1)
- Comparison of monitored data with Oregon Ambient Benchmark Concentrations (§3.1, §3.7.3)

Finding #4: Air pollutants of concern in HVAC outdoor ventilation air can be reduced to levels substantially below urban background and levels of health concern.

Primary evidence:

- Modeling of air cleaning systems with design informed by PPS mechanical contractors, data from literature, data from air cleaning sorbent manufacturers (§3.7.3)



Finding #5: A review of published literature suggests that, designed properly, incorporating vegetation and/or sound barriers near traffic exposed areas can reduce concentrations of air pollutants 15-60%.

Primary evidence:

- Review of literature of air quality impacts of tree barriers/sound walls along open roads (§3.8)

Site airflow modeling and mitigation:

Modeling has been successfully generated via virtual means. Construction of scaled HTMS and neighboring area is underway. Experimental cases have been identified.

Key recommendations:

Recommendation #1: Student outdoor activities be limited at HTMS, especially during high traffic periods.

Rationale: Outdoor air quality at the site is impacted by I-5 traffic. 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.

Recommendation #2: The HVAC system be designed to include at least MERV16 filtration and dedicated sorbent beds capable of maintaining recommended media-air contact times for gas-phase pollutant removal.

Rationale: Filtration and sorption (chemi- and/or physi-sorption) are two proven technologies for treatment of particle and gas phase air pollutants. These systems require maintenance that is reasonably consistent with ongoing practices in PPS schools.

Recommendation #3: The HVAC system be designed such that outdoor ventilation air intakes are sited as far from I-5 as possible.

Rationale: Monitoring at HTMS indicates the site is impacted by emissions from the freeway and that levels of air pollutant are reduced with increasing distance from the freeway. Siting ventilation intake far from the freeway will reduce the levels of air pollutants introduced to the HVAC system, improving indoor air quality, reducing system maintenance needs, and improving resilience.

Recommendation #4: The building be evaluated/commissioned for HVAC balancing and building airtightness to minimize infiltration, especially along those portions of the building facing I-5.

Rationale: Outdoor air can enter a building via ventilation or infiltration, the latter where outdoor air enters the building due to pressure difference across the building enclosure via cracks, gaps, or openings. It is recommended that the building shell facing I-5 be weatherized (made airtight) and rooms facing I-5 be operated at slightly positive pressure.

Recommendation #5: The efficacy of the air cleaning system be monitored periodically for breakthrough of gas-phase compounds and confirmation of removal efficiency of particulate matter as part of an air quality management plan for HTMS.

Rationale: Gas-phase air treatment is subject to considerable uncertainty, as removal efficiencies provided by the manufacturer are estimates and cannot account for site-specific conditions. We suggest quarterly monitoring of VOCs via TD-GC-MS to verify expected removal efficiency and to evaluate for sorbent breakthrough. Particulate matter sensors should be installed permanently in several areas of the school in order to assess HVAC particulate matter removal performance on an on-going basis.



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2 Summary of approach and progress to date

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. Portland State University has completed Phase I of the proposed project (start date February 1, 2018). This phase of the project includes: 1) deployment of an air quality monitoring campaign at the school site, 2) advising regarding the design of the building heating, ventilation and air-conditioning (HVAC) system and building renovation, and 3) initiation of site model development for wind-tunnel tests to characterize site airflows and possible outdoor air quality mitigation strategies.

The project proposal included a review of several prior studies of air toxics in Portland, including prior studies conducted at Harriet Tubman Middle School. A brief summary of our integrated analysis of prior



studies indicates that two significant air pollution concerns have been identified for Tubman Middle School. The first concern that arises from the existing data is the measurement of elevated cadmium levels in particulate matter less than 10 microns in diameter (PM10) at Tubman by the 2009 EPA School Air Toxics Project. Cadmium was also elevated in moss collected by the US Forest Service in 2013 in the vicinity of Tubman Middle School. The USFS moss study led to the identification of art glass manufacturers as significant emitters of cadmium in Portland. One of these manufacturers was located west of Tubman Middle School. This facility is no longer in operation. Other metals (manganese and nickel) were also elevated but well below EPA's screening levels.

The second air pollution risk identified for Tubman MS is its proximity to a heavily trafficked freeway. While EPA School Air Toxics Project measured numerous chemicals associated with vehicle exhaust and concluded that none of the measured vehicular air toxins were above the level of concern, this approach to assessing risk from freeway emissions is problematic. The EPA analysis is based on conformity to the Clean Air Act which identified risk from specific toxins and not the complex mixtures of air pollutants emanating from roadways/freeways.

The summary of the prior literature review conducted for Harriet Tubman Middle School was that **the primary risks to future occupants of Tubman MS related to ambient air quality are due to freeway emissions. The study described here is designed to assess the level of this risk relative to Portland's urban background and to summarize recommendations possible to date for mitigating indoor and outdoor air pollution.**

Outcomes and current state the Phase I of the project to be conducted by Portland State University are:

- Summary of outdoor air pollution at Tubman Middle School
 - Comparison with available standards and urban background
- Estimate effectiveness of potential mitigation strategies
 - Recommend building technologies to mitigate indoor air pollution
 - Recommend approaches for mitigation of outdoor air pollution
 - Preliminary (April 2018) – to inform mitigation options
- Wind tunnel model development, strategy

2.2 Rationale for deployment in Harriet Tubman Middle School

Portland State University conducted site visits at Harriet Tubman Middle School in January of 2018 to evaluate possible locations for rapid deployment of air quality monitoring equipment. Through



discussions with PPS administration, it was agreed that a room inside the school with an exterior louvre that opened facing the southwest (the “greenhouse”) would serve as a base of operation for the initial phase of the study. This location was chosen as it enabled i) rapid deployment by way of resolving the need for provision of electricity, shelter, and temperature control for air quality monitoring, ii) provided a conservative estimate of air quality measurements as it is in proximity to I-5, iii) provided security for maintenance of instrumentation, and iv) provided a representation of outdoor air in a location reasonably consistent with current (pre-renovation) locations of HVAC outdoor air intakes.

On Feb 1st, the indoor base of operation was outfitted with a 20.3 cm diameter stainless steel duct with a continuously operating fan that induced a flow of $\sim 50 \text{ m}^3/\text{h}$ of outdoor air through the duct and into the indoor space. This created a high refresh rate in the sampling inlet to ensure that air sampled by monitors was representative of outdoor conditions near the southwest face of the building. Photographs of the sample inlet location and interior installation of the inlet are shown in Figure 2.

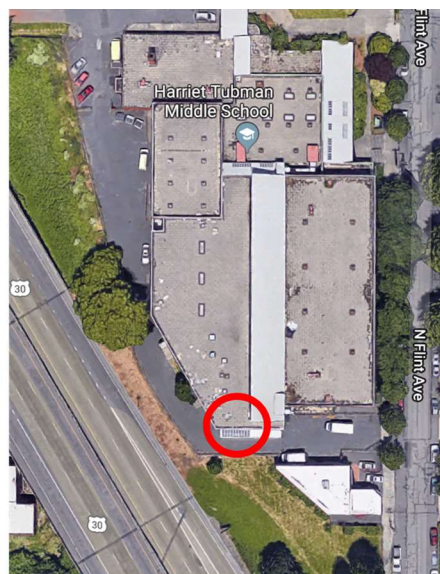


Figure 2. Left: Installation of steel inlet duct in indoor location inside HTMS. The leftmost component of the inlet duct is a continuously operating ventilation fan that maintained a high refresh rate inside the duct. Right: Approximate location of sampling inlet on HTMS building. Note that all air quality sampling conducted here is that of outdoor air; Phase II of the project will include indoor air monitoring.

The existing building also enabled deployment of meteorological monitoring in close proximity to the outdoor air inlet. On the rooftop (within the red circle shown in Figure 1), PSU deployed a weather station and sonic anemometer to characterize site air flows, wind direction, wind speed, temperature, relative humidity, rainfall, and barometric pressure. Measurement of these parameters provides context for



assessing the origin of air pollution as from the freeway by evaluating time-series data of air pollution and meteorological conditions. A picture of the weather station deployed on the rooftop of Harriet Tubman Middle School is shown in Figure 3.



Figure 3. Installation of weather station on HTMS rooftop.

While the intensive air quality monitoring focused on the deployment inside the location of the school shown in Figure 2, monitoring was also conducted using portable sensors to create spatial “maps” of air pollutants (see Section 3.4) and monitors were deployed for a period to the eastern face of the school (see Section 3.6). Finally, air pollutant concentrations of those same compounds monitored at HTMS were collected from various sites around Portland to provide context to the data collected at HTMS. The data from other sites in Portland was gathered to provide comparisons to other urban sites, including other sites in close proximity to freeways and to an urban site a greater distance from a freeway. These additional efforts are discussed in further detail and results presented in this report.

2.3 Deployment schedule

Table 1 summarizes the deployment of monitors to the Harriet Tubman Middle School for monitoring of outdoor air around the building. A more detailed description of instrument make and model is provided in Table 2. A summary of the quality assurance/quality control plan is provided in Table A1 in Section 6.2.

Table 1. Summary of deployment schedule for Phase I monitoring at Harriet Tubman Middle School

				Week 1				Week 2				Week 3				Week 4				Week 5							Week 6				Week 7																		
	Feb.			March																												April																	
	26	27	28	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Weather station - T, HR, wind (speed,dir)																																																	
Sonic anemometer - wind parameters																																																	
Magee - BC - Greenhouse																																																	
Magee - BC - Flint																																																	
Teledyne - NOx + O3 -Greenhouse																																																	
Teledyne - NOx - Flint																																																	
CO monitor																																																	
Passive NO2 monitoring																																																	
Fluke - PM																																																	
OPS - PM																																																	
PurpleAir Sensors (I5-N; I5-S; FI-N; FI-S) - PM																																																	
SMPS - UFP																																																	
Ptrak - UFP																																																	
ARA 1 - metals																																																	
ARA 2 - mass																																																	
TD-GC-MS - VOCs 24hrs sampling																																																	
TD-GC-MS - VOCs 1 hr sampling																																																	
PTR-TOF-MS - VOCs real time																																																	

2.4 Monitors employed in Phase I monitoring at HTMS

This section summarizes the monitoring devices deployed and used in the characterization of outdoor air quality at Harriet Tubman Middle School, Phase I. Figure 4a-e provide pictures of the monitors used and the nature of their installation. As described in Section 2.2, the emphasis of this monitoring campaign was on **rapid deployment** to inform the site renovation and heating, ventilation, and air-conditioning system design.

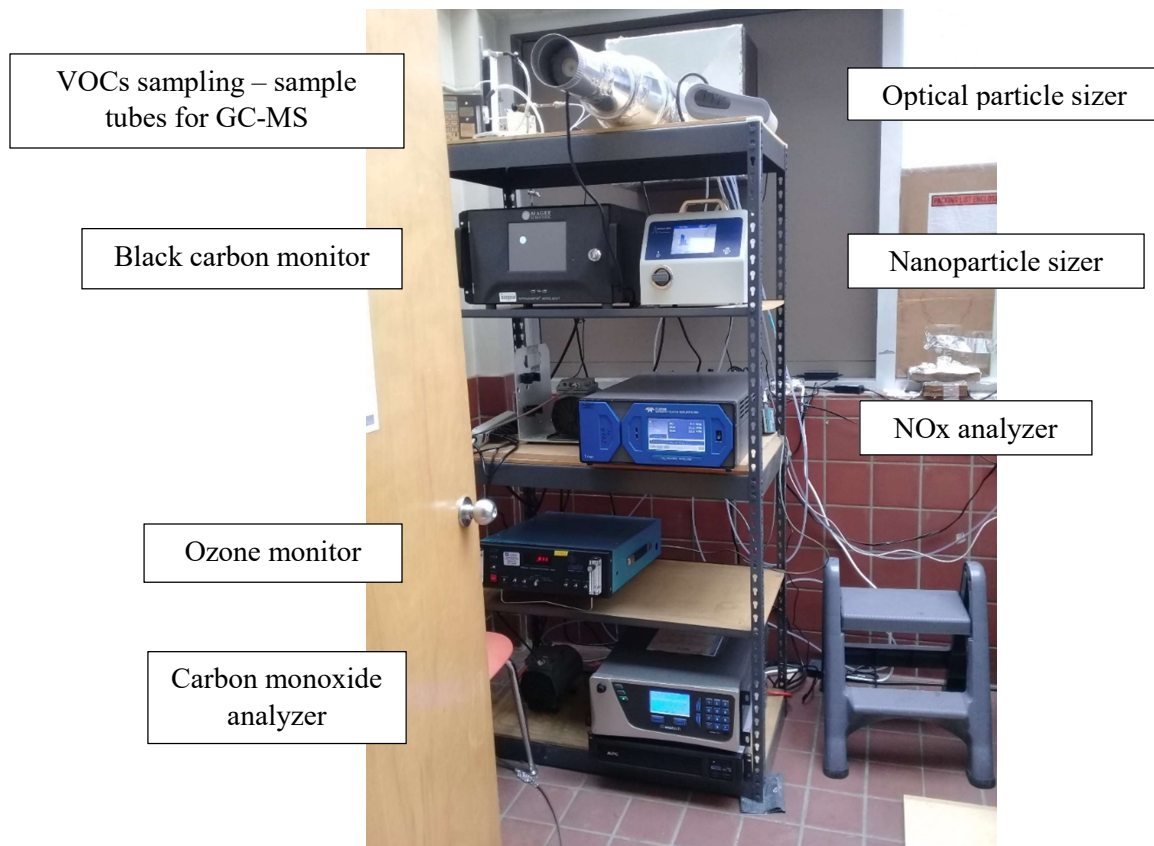


Figure 4a. Installation of all instruments in the “greenhouse” at Harriet Tubman Middle School



Figure 4b. Weather station between the two ARA samplers at Harriet Tubman Middle School (picture on the left) and an ARA sampler (PM10) (picture on the right)



Figure 4c. Volatile organic compound monitoring systems. The PTR-TOF-MS (picture on the left) and sampler and sorbent tubes for GC-MS (picture on the right) in the greenhouse at Harriet Tubman Middle School.



Figure 4d. TD-GC-MS in the lab at PSU for the analysis of sorbent tubes

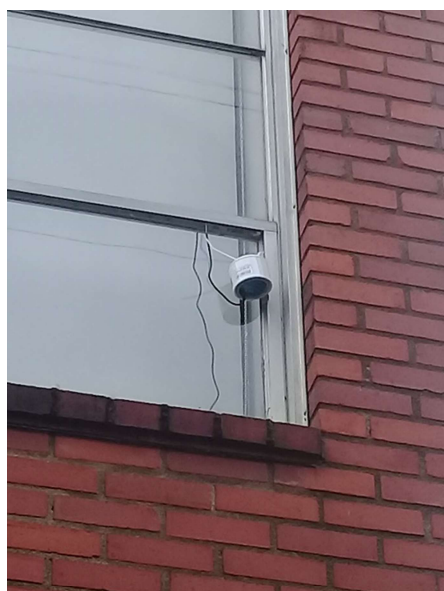


Figure 4e. PurpleAir sensors on Flint-south side (picture on the left) and on I-5-south side (picture on the right)


Table 2. Summary of monitors deployed at Harriet Tubman Middle School.

Parameters Monitored	Instrument Manufacturer/Make	Method of measurement
Nitrogen oxide, nitrogen dioxide	Teledyne T200P Teledyne T200	Chemiluminescence detection; concentration range: 0-50 ppb to 0-20 ppm
Carbon monoxide	Ecotech Serinus 30	Non-Dispersive Infrared Spectrophotometry (NDIR); concentration range: 0-200 ppm
Black carbon	Magee Scientific 55	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 $\mu\text{g}/\text{m}^3$
PM 2.5 (mass/metals) PM 10 (metals)	ARA Instrument	Sampling ambient air through a PTFE filter via a pump for subsequent analysis
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	PTR-TOF-MS	Proton Transfer Reaction Mass Spectrometry with Time-Of-Flight analyzer; limit of detection = 10 pptv
Volatile organic compounds	Grab samples + GC-MS	Compounds trapped on sorbent tubes, desorption in gas chromatography coupled with Mass Spectrometry
Site meteorology	Campbell Scientific CSAT3 Sonic Anemometer	Generation and measurement of sonic pulses to compute 3-D wind speeds and temperature with high time resolution
Site meteorology/weather	AcuRite 02064	Measurement of temperature, relative humidity, wind direction, wind speed

3 Results & Discussion

3.1 Air toxics compared to Oregon Ambient Benchmark Concentrations

Table 3 shows the determination of volatile organic compound (VOC) concentrations performed using two different methods: gas chromatography coupled with mass spectrometry (GC-MS) and proton transfer reaction – time of flight - mass spectrometry (PTR-TOF-MS).

For the GC-MS (Agilent Technologies), VOCs were sampled during the month of March (3/12/18-3/30/18) on a daily schedule with sample tubes containing two different sorbents. For each sample tubes, samplers ran for ten occurrences, for six minutes each occurrence, within a twenty-four hour period. Each twenty-four hour period began at noon. The sample flow rate was 50 mL/min.

For the PTR-MS (Ionicon, PTR-TOF1000), VOCs were sampled during the months of March and April (3/15/18-4/15/18) continuously (every two seconds) with a flow rate of 15 mL/min.

For the sampling period, the average concentrations of VOCs were below the Oregon Ambient Benchmark Concentrations (ABC), except for benzene, acrolein, and naphthalene, which showed concentrations higher than ABC.

Table 3. Summary of VOCs concentrations at Harriet Tubman Middle School – Comparison with Oregon Ambient Benchmark Concentrations (ABC) and Portland Urban Background from ODEQ Humboldt (ODEQ data is provisional). Values in red are those elevated above Oregon ABCs.

Chemical name	Sources *	PDX BG** (µg/m ³)	ABC# (µg/m ³)	Tubman average concentrations all days (µg/m ³)	Tubman average concentrations weekdays 7AM-4PM (µg/m ³)	Analytical Method
acrolein	burning of fuels (gasoline/oil), burning of organic matter (as tobacco), ...	0.25	0.02	0.34***	0.40***	PTR-TOF-MS
benzene	burning of coal and oil, gasoline service stations, and motor vehicle exhaust	0.59	0.13	1.22 / 0.87	0.91 / 1.02	TD-GC-MS / PTR-TOF-MS



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Chemical name	Sources *	PDX BG** ($\mu\text{g}/\text{m}^3$)	ABC# ($\mu\text{g}/\text{m}^3$)	Tubman average concentrations all days ($\mu\text{g}/\text{m}^3$)	Tubman average concentrations weekdays 7AM-4PM ($\mu\text{g}/\text{m}^3$)	Analytical Method
1,3-butadiene	motor vehicle exhaust	traces	0.03	traces	traces	TD-GC-MS
chloroform	manufactory, swimming pools, pulp and paper mills, hazardous waste sites, sanitary landfills	traces	98	0.09	0.08	TD-GC-MS
n-hexane	used as solvent to extract edible oils, used as solvent for glues, varnishes, inks	0.46	7000	0.67	0.73	TD-GC-MS
methanol	used as solvent for inks, resins, adhesives and dyes; automobile exhaust	traces	4000	8.73	9.58	PTR-TOF-MS
naphthalene	burning of coal gas, diesel and oil, use of mothballs, some manufactory	traces	0.03	0.13 / 0.26***	0.12 / 0.31***	TD-GC-MS / PTR-TOF-MS
tetrachloroethylene	used for dry cleaning and textile processing, as a chemical intermediate, and for vapor degreasing in metal-cleaning operations	traces	35	0.24	0.27	TD-GC-MS
toluene	automobile emissions, paints, adhesives, cigarette smoke	1.12	400	1.39 / 1.31	1.43 / 1.69	TD-GC-MS / PTR-TOF-MS



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Chemical name	Sources *	PDX BG** (µg/m³)	ABC# (µg/m³)	Tubman average concentrations all days (µg/m³)	Tubman average concentrations weekdays 7AM-4PM (µg/m³)	Analytical Method
trichloroethylene	industrial degreasing operations	traces	0.5	traces	traces	TD-GC-MS
xylene (o-, m-, p-xylene)	industrial sources, auto exhaust	1.28 (3 isomers)	700	1.02 (p-xylene) / 1.91 (xylenes + ethylbenzene)	1.07 (p-xylene) / 2.15(xylenes+ethylbenzene)	TD-GC-MS / PTR-TOF-MS
ethylbenzene	gasoline, pesticides, solvents, carpet glues, varnishes, paints, and tobacco smoke	0.3	0.4	0.25	0.25	TD-GC-MS
trimethylbenzene (1,3,5-)	Additive and component of some aviation gasoline blends, component of coal tar	traces	NA	0.099 (1 isomer) / 1.31 (all isomers+ethyltoluene)	0.097(1 isomer) / 1.60 (all isomers+ethyltoluene)	TD-GC-MS / PTR-TOF-MS
Ethyl toluene	used for the production of specialty polystyrenes.	traces	NA	0.97	0.99	TD-GC-MS
Tetra methylbenzene (1,2,3,5-)	used as chemical intermediate	NA	NA	0.09 (1 isomer) / 0.60 (all isomers)	0.095 (1 isomer) / 0.72 (all isomers)	TD-GC-MS / PTR-TOF-MS
methyl ethyl ketone	used as a solvent in processes involving gums, resins, cellulose acetate, and cellulose nitrates	0.69	NA	0.52 / 0.84	0.64 / 0.99	TD-GC-MS / PTR-TOF-MS

* from various U.S. EPA resources

** Background PDX concentration for comparison from recent monitoring data provided by Oregon DEQ at Humboldt International School

Oregon Ambient Benchmark Concentration

*** calculated via mass correction factor (transmission curve) for PTR-TOF-MS

NA: Not available

3.2 Ambient particulate matter metals data compared to Oregon Ambient Benchmark Concentrations (ABC)

Particulate matter (PM₁₀ and PM_{2.5}) was sampled during the month of March (3/9/18-3/28/18) on an every other day schedule with ARA Inc. N-FRM Samplers with PTFE filters (46.3 mm, 2 µm pore). For each filter, samplers were run for 24 hours starting at midnight with a flow rate of 1 m³/hr. Filters were sent to Chester Analytical (Tigard, OR) for testing. **For the sampling period, the average concentrations of toxic metals were significantly below the Oregon Ambient Benchmark Concentrations, except for arsenic.** Arsenic has been found to be at elevated levels in urban background air in the Portland area. Two blanks were collected. Toxic metals in the blanks were significantly below the average concentrations and/or at the uncertainty level. Data are summarized in Table 4.

Table 4. Summary of metals analysis conducted at Harriet Tubman Middle School.

Toxic Metal	<i>Oregon ABC (1 in million risk) ug/m3</i>	PM₁₀ µg/m3 (uncertainty) n=10	PM_{2.5} µg/m3 (uncertainty) n=7	Method
Arsenic	<i>0.0002</i>	0.0009 (0.0003)	0.0012 (0.0003)	XRF
Cadmium	<i>0.0006</i>	<DL	NA	ICP-OES, DL=0.0007
Cobalt	<i>0.1</i>	0.0001 (0.0013)	<DL (0.0013)	XRF
Lead	<i>0.15</i>	0.002 (0.0005)	0.008 (0.0005)	XRF
Manganese	<i>0.09</i>	0.0230 (0.0018)	0.0143 (0.0013)	XRF
Mercury	<i>0.3</i>	0.0001 (0.0005)	<DL (0.0005)	XRF
Nickel	<i>0.004</i>	0.0019 (0.0003)	0.0014 (0.0003)	XRF

XRF = X-ray fluorescence

ICP-OES = Inductively coupled plasma – optical emission spectroscopy

Detailed results of the metals present in PM₁₀ and PM_{2.5} are provided in the appendix in Section 6.1. Day to day variation was observed in the measurements of metals, however, most values were below the Oregon Ambient Benchmark Concentrations and further exploration of the cause of variability was not in the scope of this project.



3.3 Monitoring at greenhouse

3.3.1 Variation in outdoor air quality at HTMS

During the month of March 2018, black carbon, carbon monoxide, ultrafine particles ($d < 100\text{nm}$), $\text{PM}_{2.5}$, PM_{10} , several volatile organic compounds, and nitrogen oxides were monitoring continuously from the Tubman Middle School greenhouse. Outdoor air was drawn through a stainless steel duct as described in Section 2.2. Air pollution monitors sampled air from this duct. Meteorological parameters were also monitored during this period on the roof of the building. Figure 5 shows the wind pattern during the monitoring period (March – April 4, 2018). The dominant winds were from the SE, SW with a significant flow from the NW. Near-continuous measurements of air pollutants along with wind speed and direction allow us to identify the location of potential pollution sources impacting the Tubman site.

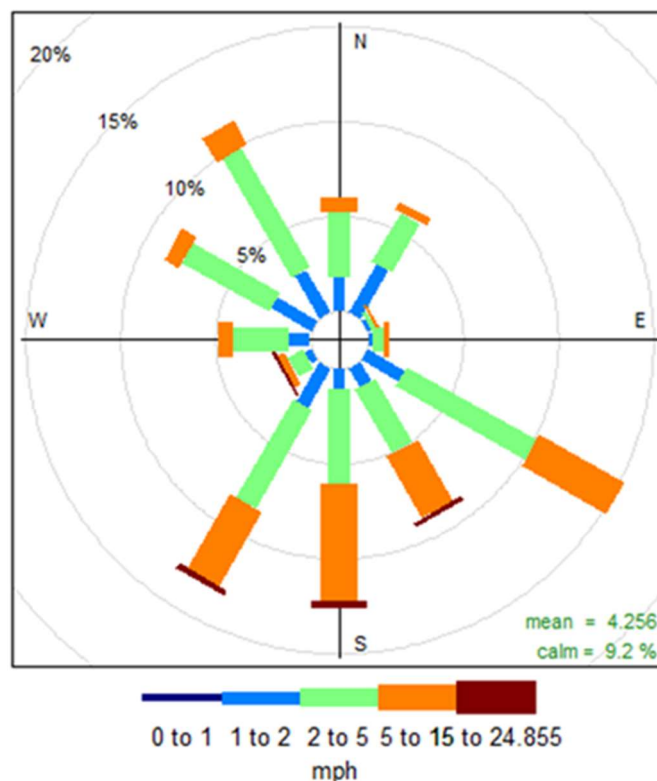


Figure 5. Frequency of wind counts by direction (%) March-April 4, 2018

We examined the temporal variation of pollution levels with respect to time of day and day of week. Figure 6, clearly shows a pattern consistent with a traffic-related pollutant with elevated levels during rush hours.

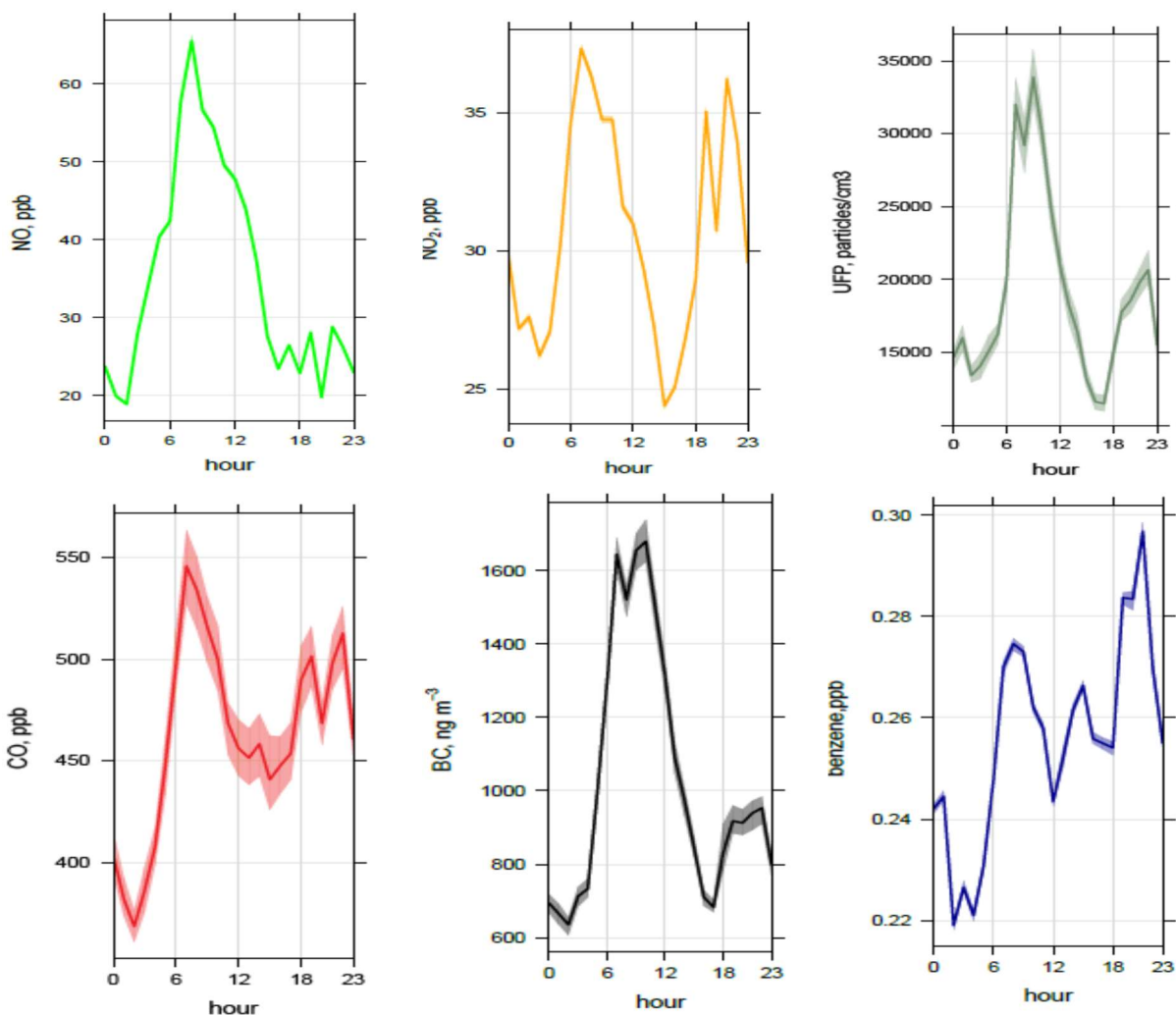


Figure 6. Diurnal variation of pollutants monitored at Tubman Middle School, averaged over available data, March and early April 2018. Peak levels correspond to rush hour periods. Error bands are 95% confidence intervals of means.

The evening rush hour levels are reduced compared to morning rush hour, potentially due to higher dilution with higher afternoon windspeed and mixing height. Weekday levels are significantly higher than weekend levels (Figure 7) for pollutants monitored (NO, NO₂, ultrafine particles, CO, black carbon, and benzene).

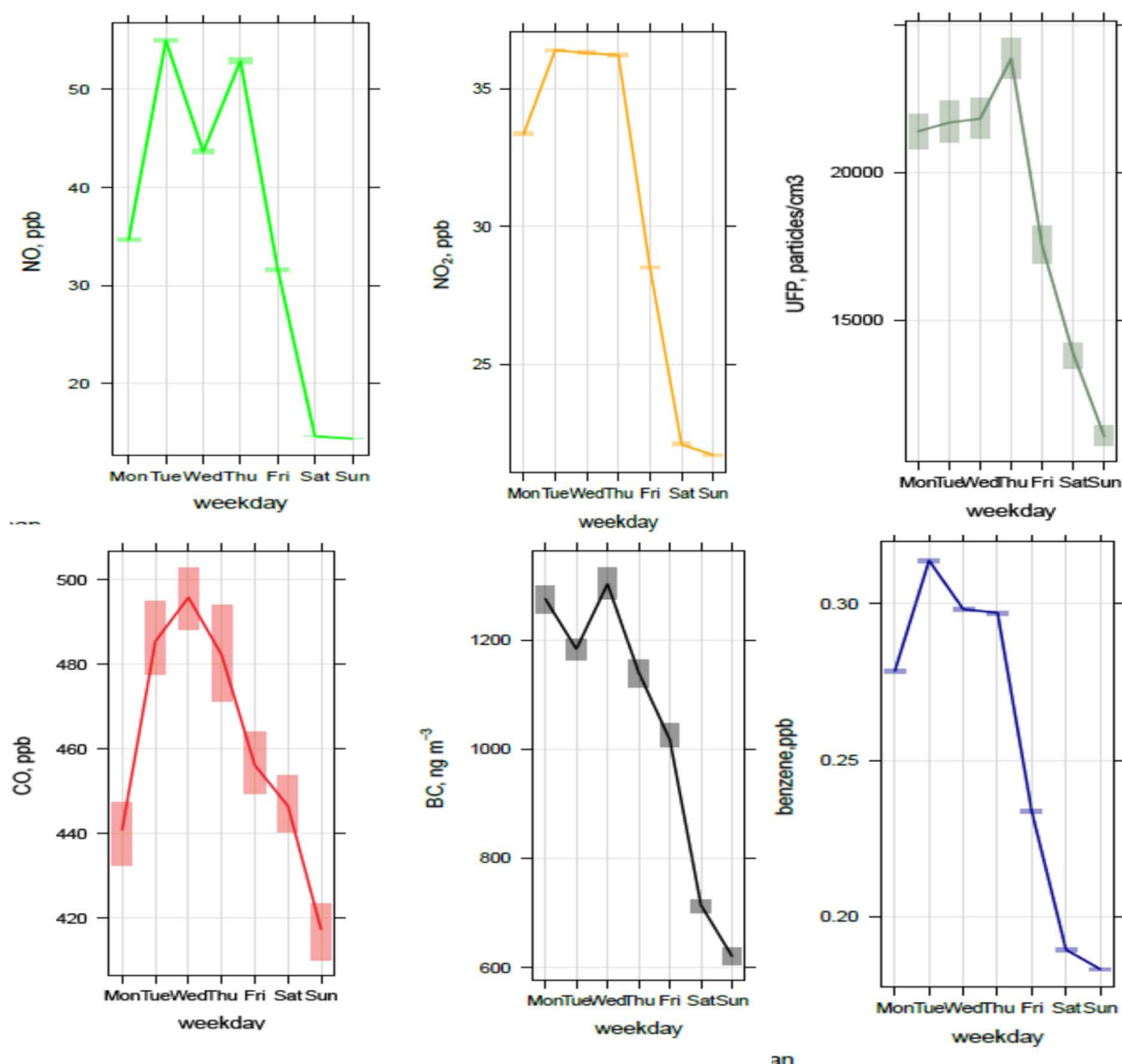


Figure 7. Day of week variation of pollutants monitored at Tubman Middle School, averaged over available data, March and early April 2018. Error bands are 95% confidence intervals of means.

3.3.2 Polar plots

We have used polar plots to analyze how wind direction influences the level of pollutants. In the figures below (Fig 8a-c), concentrations of the pollutants are plotted with respect to concentration (color) and the direction wind is coming from. For example, if the pollutant level is low compared to average for the period and the wind is coming from the North during that period, it would be plotted with a blueish color on the North side of the center of the plot. The distance away from the center reflects the wind speed. 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. In the plots below of pollutants that are influenced by combustion exhaust, there is a distinct source west of the Tubman site. Wind coming from the east has generally lower levels of pollutants. This contrast is especially true for short-lived pollutants such as nitrogen oxides, black carbon and ultrafine particles.

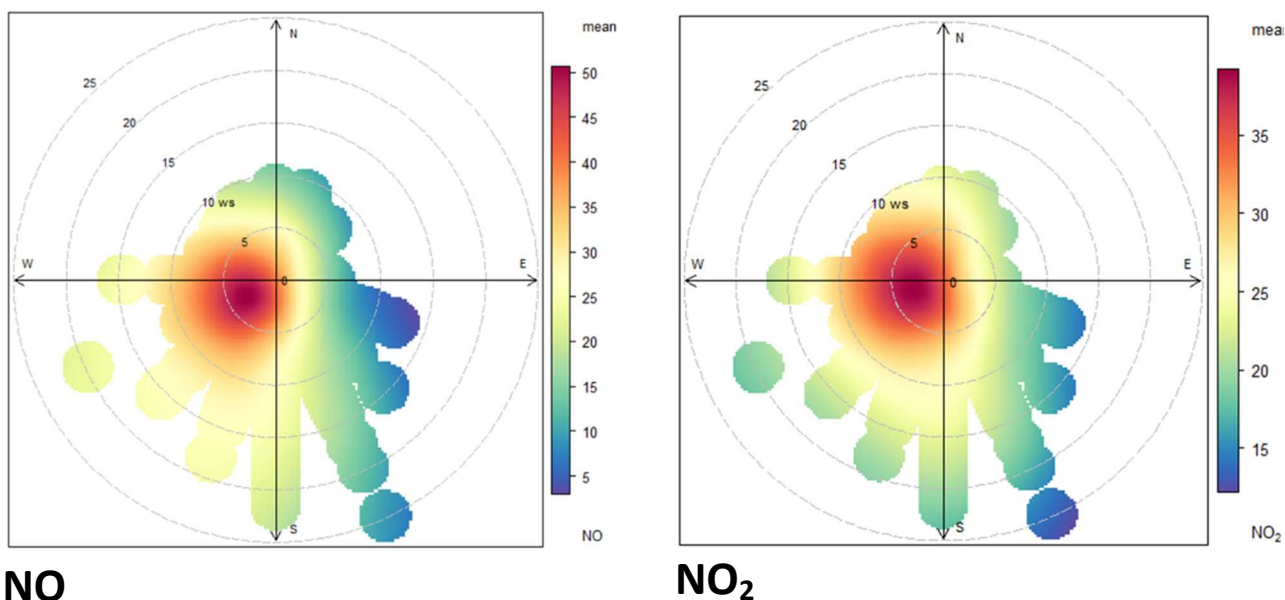
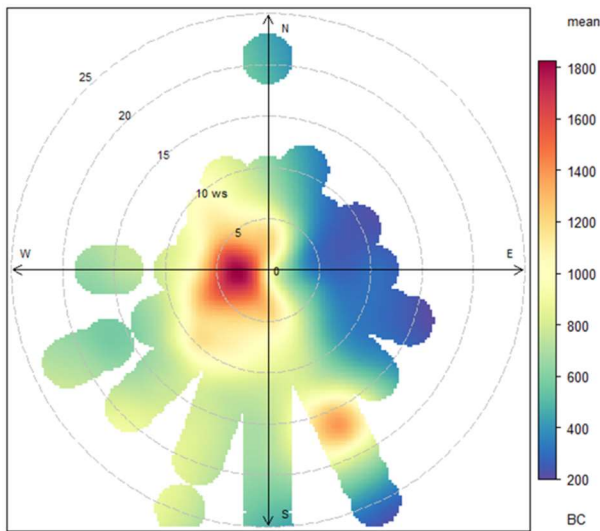
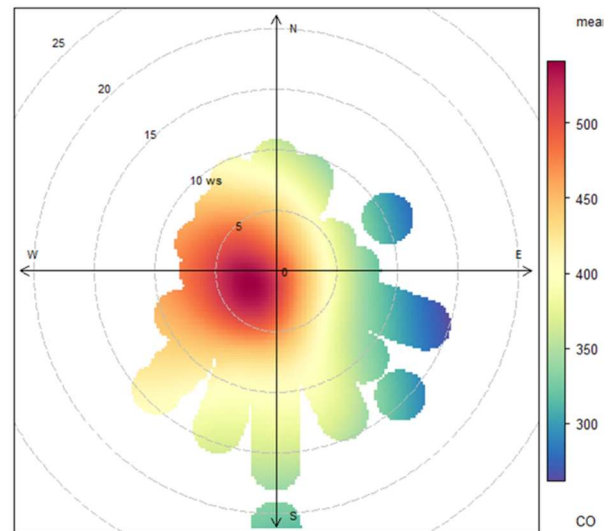


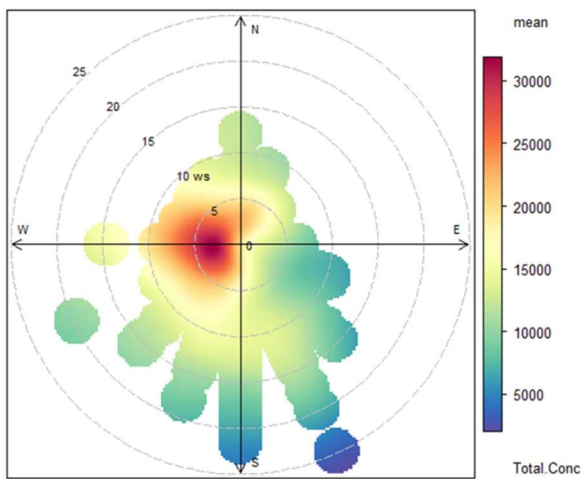
Figure 8a. Polar plots of continuous data using meteorological data collected at Tubman Middle School (wind speed is mph; NO, NO₂ in ppb)



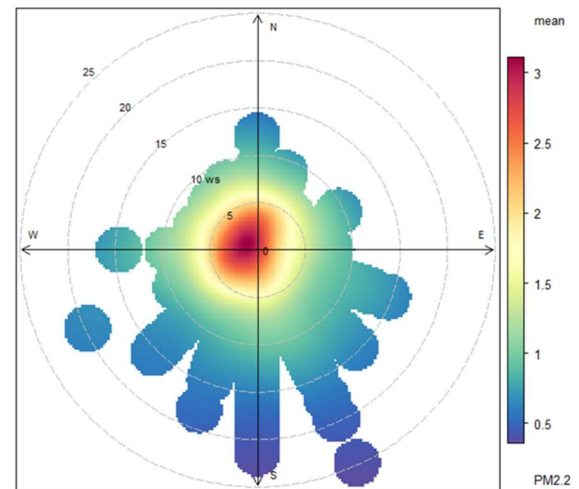
BC



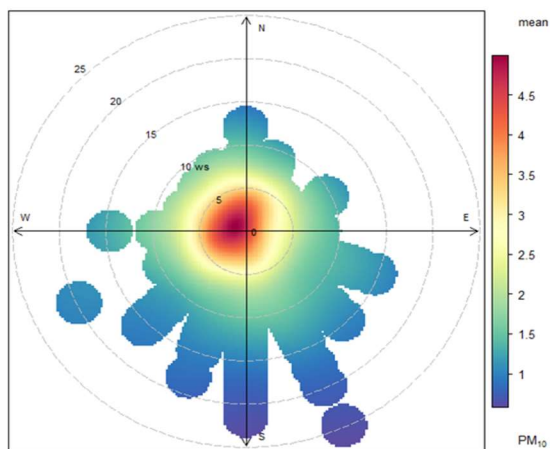
CO



UFP



PM 2.2



PM 10

Figure 8b. Polar plots of continous data using meteorological data collected at Tubman Middle School (wind speed is mph; CO in ppb; BC in ng/m³; UFP in particle/cm³; PM_{2.2}, PM₁₀ µg/m³)

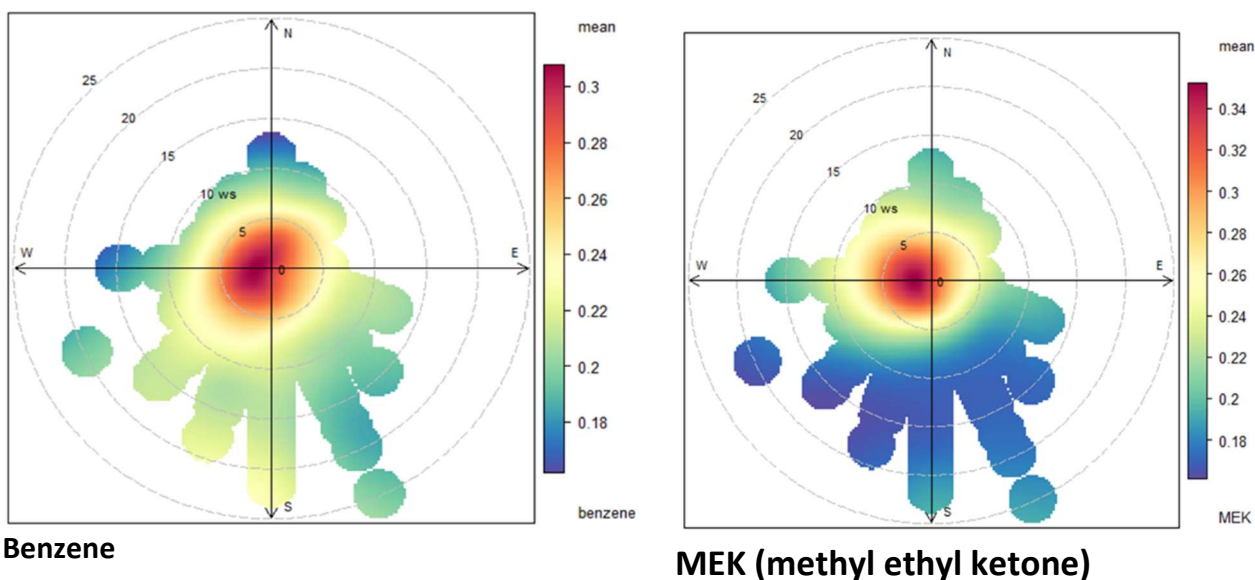


Figure 8c. Polar plots of continuous data using meteorological data collected at Tubman Middle School (benzene, MEK in ppb)

3.4 Spatial variation investigations

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. Passive nitrogen dioxide samplers were deployed in an area roughly 0.1 km² around the school on both sides of the I-5 freeway. Nitrogen dioxide monitoring has been used in many epidemiological studies as a tracer of combustion exhaust. Nitrogen dioxide samplers are thimble-sized devices mounted about 2.5 meters above ground and exposed to the air for 10-14 days. After laboratory analysis, each sampler gives the average concentration of nitrogen dioxide at that site. The spatial variation of the nitrogen dioxide at each site averaged over (February 27-March 12th, 2018) clearly shows the influence of the freeway on the nitrogen dioxide levels near Tubman, with higher levels closer to the freeway (Figure 9). As a tracer of exhaust, and based on numerous published studies, we can anticipate that the levels of all combustion related pollutants will vary in a similar way.

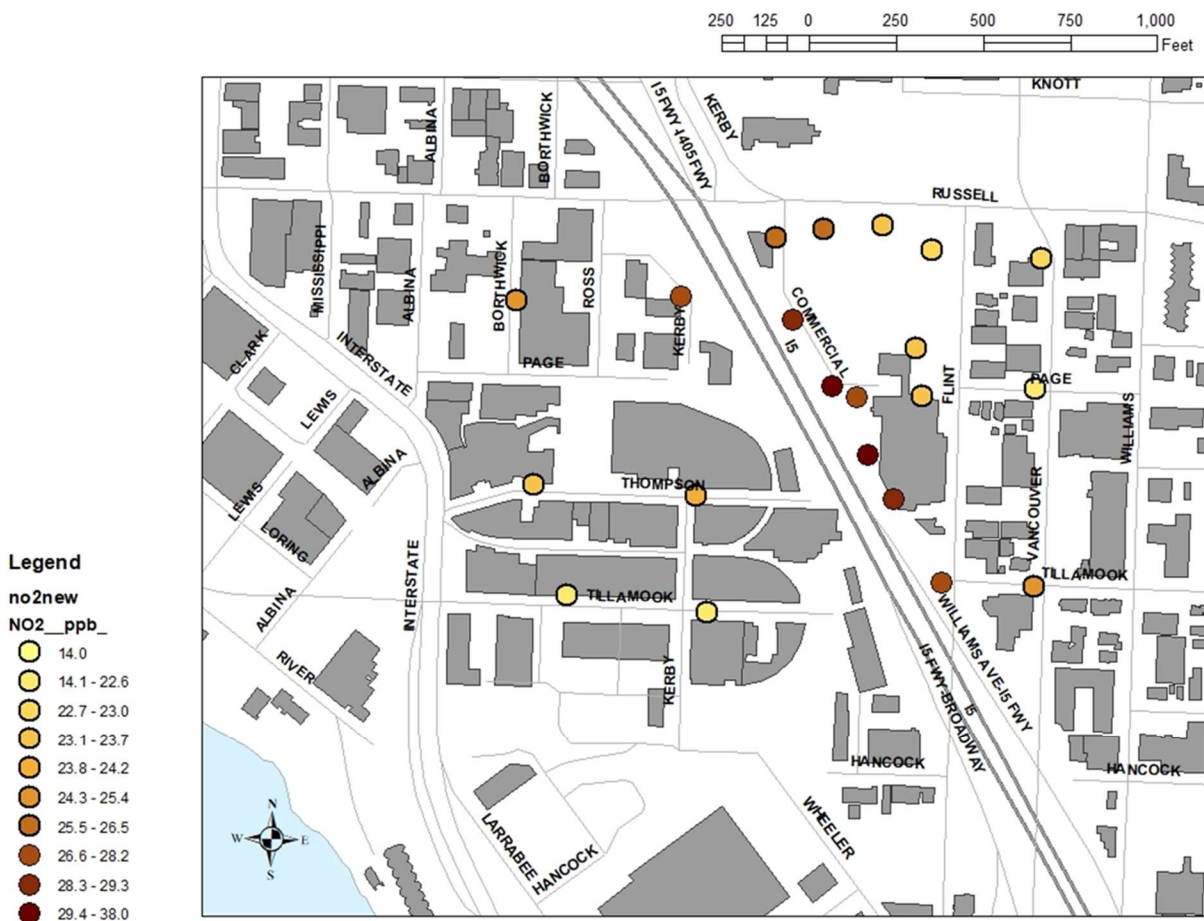


Figure 9. Summary of passive NO₂ monitoring deployment conducted from February 27th-March 12th, 2018)

We also conducted spatial surveys of ultrafine particles ($d < 100\text{nm}$) with a hand-held ultrafine particle sensor (TSI Ptrak). In Figure 10 below is an example of one of several transects collected (collected 4/2/18 9:40-10AM). The ultrafine data is overlaid with the nitrogen dioxide data to emphasize the correlation. This correlation suggests that the source of both pollutants is the same. Ultrafine particles are expected to be formed from combustion exhaust based on numerous published studies and are composed of a wide array of compounds.



Figure 10. Summary of passive NO₂ monitoring deployment conducted from February 27th-March 12th, 2018) overlaid with a spatial survey of ultrafine particles (UFP). Transects of UFP were collected on April 2nd, 2018.

3.5 Comparison with urban background

Most of the pollutants we have measured are not above either the National Ambient Air Quality Standards or the Oregon Ambient Benchmark Concentrations. However, 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). The N-Core site is situated to assess the general air quality of the Portland region. The polar plot below (Figure 11) shows that Tubman is impacted by a significant source to the west of the site, while SEL is mainly impacted by regionally mixed pollution coming from all directions (although there seems to be some impact from Powell Blvd north of the site).

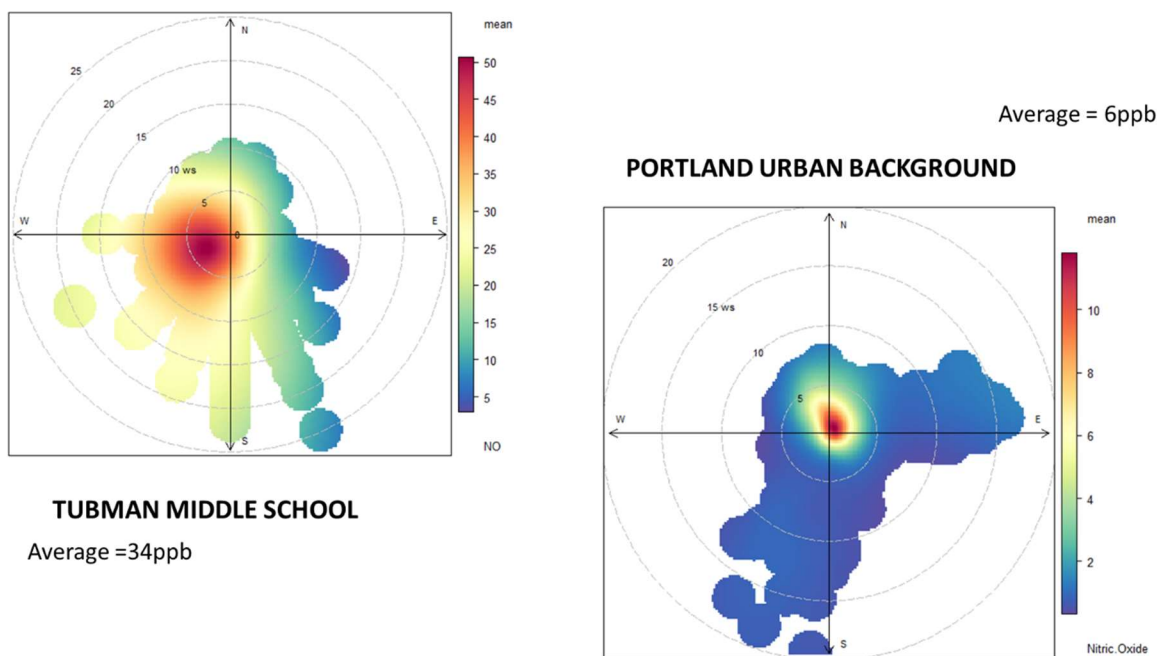


Figure 11. Polar plots of NO levels at Tubman middle school compared to that of urban background.

The bar graphs below in Figure 12 compare the levels at HTMS at two other stations, the SEL station and the Oregon DEQ I-5S roadway monitoring stations for NO, NO₂, and CO.

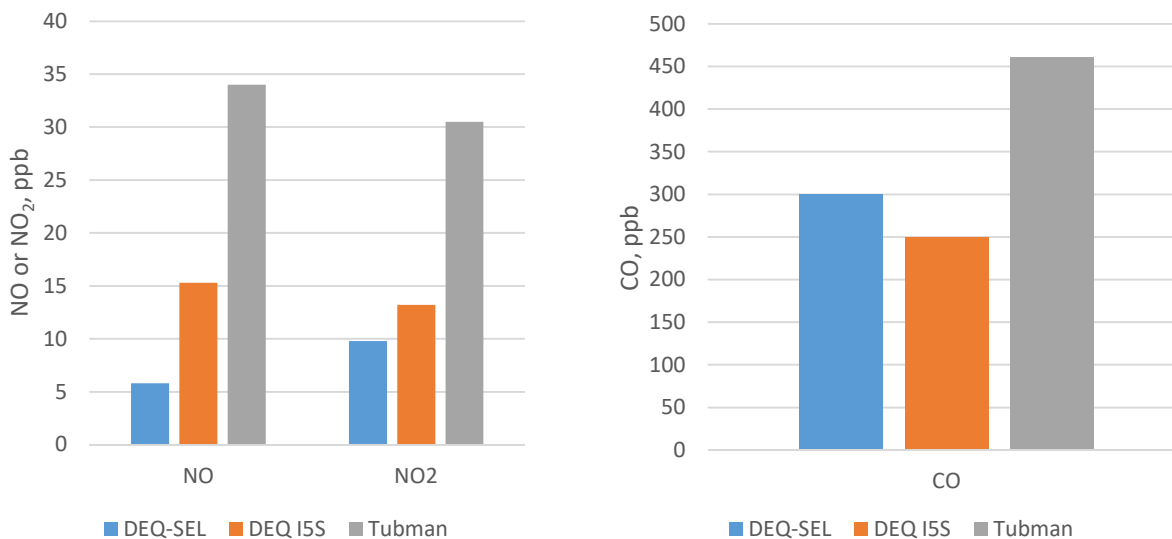


Figure 12. Comparison of NO, NO₂, and CO at Harriet Tubman Middle School to urban background



3.6 Flint vs. I-5 comparison

It is well established that freeways are a major source of outdoor air pollutants. **Therefore, one recommendation to PPS is to prioritize the source of outdoor air ventilation at Harriet Tubman Middle School to be as far away from I-5 as possible.** The logic is simple: as one moves farther away from a freeway (the source), the impact of dilution reduces levels of air pollution from vehicle emissions on that freeway. Prior studies have confirmed this finding in many studies over the past decades. For example, a study conducted by Zhu et al. (2002), summarized in Figure 11, shows evidence of this phenomenon for three measurements of air pollutants: particulate matter (PM), black carbon (BC), and carbon monoxide (CO). In this figure, concentrations are normalized to equal unity (1) at the edge of the roadway. The plot shows that at a distance of ~50 m one can observe reductions of approximately 50% of BC and CO. Note that reductions are more modest for the PM (in this case PM₁₀).

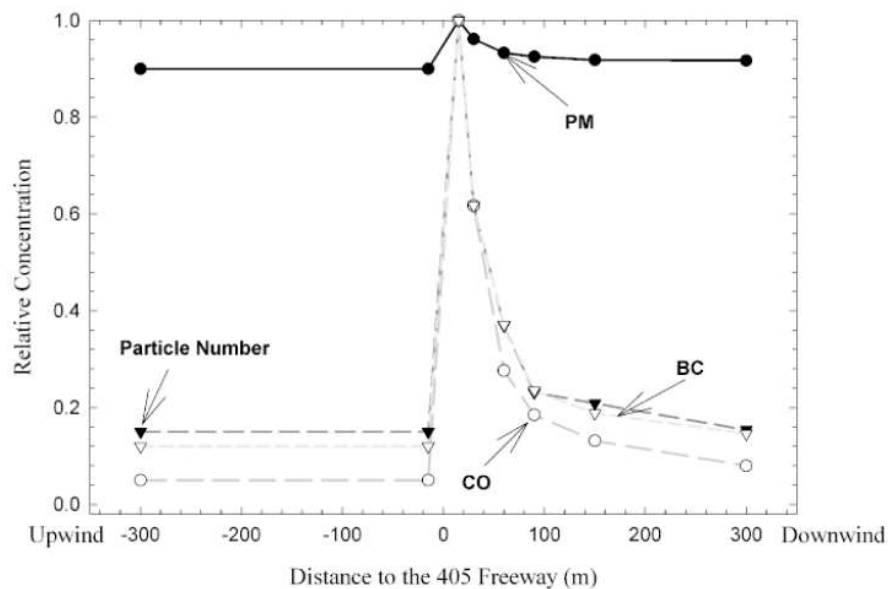


Figure 11. Impact of distance upwind and downwind a major freeway on relative concentrations of various air pollutants (PM = particulate matter, BC = black carbon, CO = carbon monoxide). PM levels were determined by a photometric instrument that was purported to be an indicator of total particle mass in the range of PM₁₀. Figure taken from Zhu et al. (2002).

To characterize the importance of such dilution effects at HTMS and to evaluate the potential benefit of siting ventilation air intakes along Flint Ave, PSU deployed two types of monitors in two locations in parallel at the Harriet Tubman Middle School site. An aethelometer (Magee, AE33) and NO_x monitor (T200, Teledyne) were deployed on the southeast side of HTMS for ~1 week period in addition to

monitoring in the greenhouse. However, because of construction activity at HTMS related to the renovation of the school, a full 1-week period could not be realized. Nevertheless, sufficient data is available from these monitors to support a robust comparison of air quality at two locations at HTMS using research grade monitoring equipment. In addition, low-cost PM sensors (PurpleAir, PA-II) were deployed to each corner of the building. Locations of these additional fixed monitors are shown in Figure 12. Our key finding from this study is that **tracers of vehicle combustion are substantially elevated on the face of the school oriented towards I-5 compared to the face of the school oriented towards Flint Ave.**

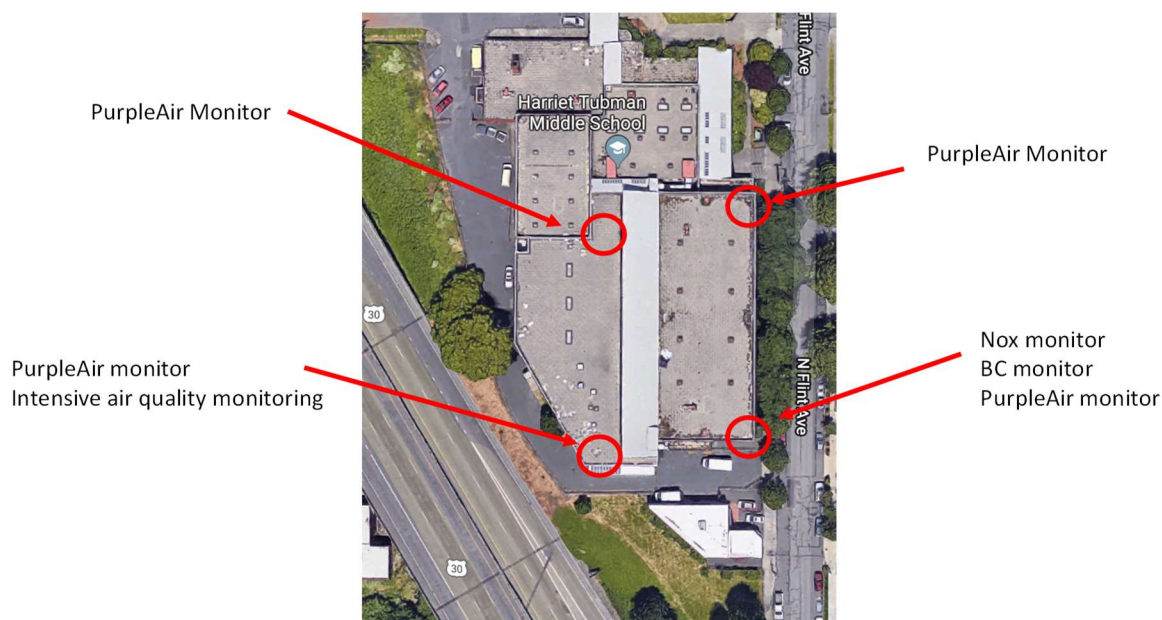


Figure 12. Location of fixed monitors for time-series monitoring at multiple spatial locations around the HTMS building.

3.6.1 Black carbon comparison: I-5 vs. Flint facades of HTMS

As discussed in Section 3.6, black carbon (BC) levels are an important tracer of vehicle combustion, especially diesel vehicles, although light duty gasoline vehicles also emit black carbon (Kamboures et al. 2013; Zheng et al. 2015). Black carbon itself is also known to be a harmful air pollutant, and studies indicate that BC may be a better indicator of harmful particulate matter substances than mass based measurements of PM. Thus, measurements of BC at HTMS serve two purposes: i) as a broader indicator of the presence of products of combustion associated with vehicle exhaust and ii) as an air pollutant of interest with respect to health impacts of degraded air quality at HTMS. Prior to this Flint vs. I-5 analysis, the paired monitors were co-located in the SW monitoring location (the “greenhouse”) to measure the



same inlet air stream; this quality assurance measure provided the means to create a correction factor across the range of black carbon levels present at the site.

Black carbon levels at the I-5 and Flint faces of HTMS are reported for the period of co-deployment from April 6-10th in Figure 13. Note that the co-deployment continued beyond April 10th, but beginning in the morning of April 10th, large heavy duty machines and vehicles were observed in the parking lot on the SW corner of HTMS; data subsequent to 06:00 on 10-April-2018 is therefore not included in this analysis. Our key finding from this portion of the investigation is that **black carbon levels are substantially elevated on the face of the school oriented towards I-5**. Note that the periods of reduced BC levels (from 4/07 – 4/08) coincide with a weekend when traffic volumes and type of vehicles are likely to be different from that of the weekday.

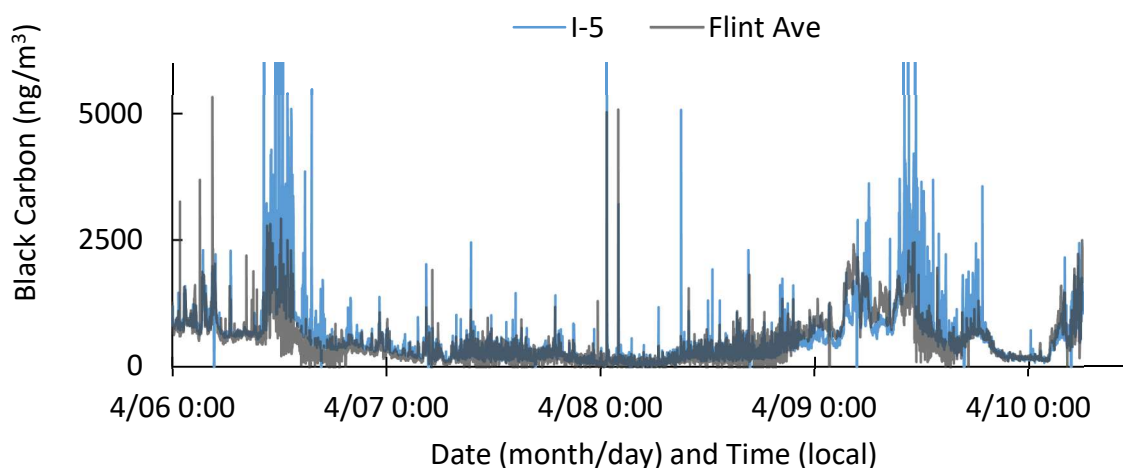


Figure 13. Summary of time-series data collected for the black carbon on the I-5 face of HTMS (blue line) and the Flint Ave. (grey line) face of the building. Note that several measurements from the I-5 time series exceed the scale of the time-series plot.

The comparison of I-5 BC levels vs. Flint Ave. BC levels is presented in Figure 14 for 24-h time averages of the concentrations reported at each location across the five-day period. From this chart, we see that the reduction in BC levels from I-5 to Flint is apparent on two of the three weekdays for which parallel monitoring took place. Note that April 7th and April 8th are both weekend days and BC levels are more consistent on a 24-h averaging basis.

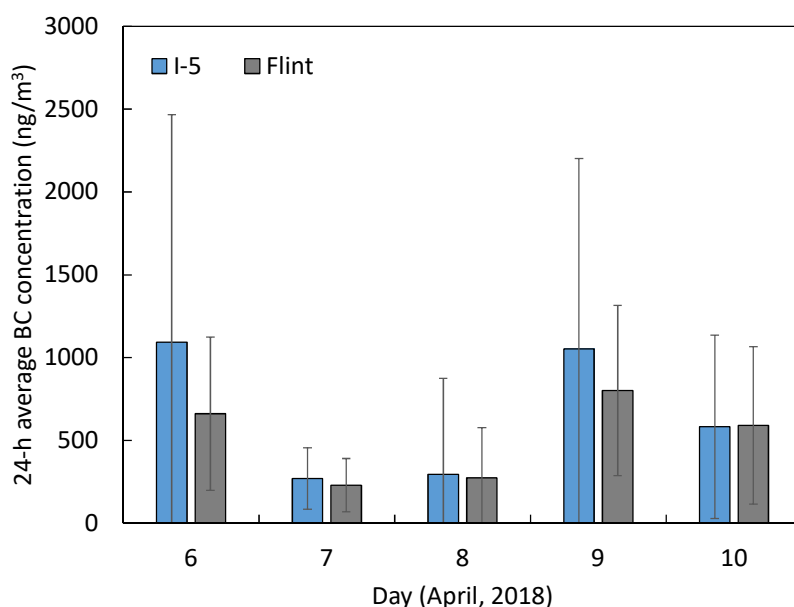


Figure 14. Comparison of 24-h average black carbon levels along I-5 and Flint faces of Harriet Tubman Middle School. Note that 7-8 April are weekend days. Error bars reflect standard deviations across the 24-hour period.

Further analysis of the temporal dependence of the relationship between I-5 and Flint BC levels is shown in Figure 15, where hourly averages at each location (I-5 and Flint) are shown for all days. Note that during the period beginning at approximately 9 AM, BC levels at I-5 appear to be elevated over that of Flint Ave and remain elevated until the evening (~7 PM).

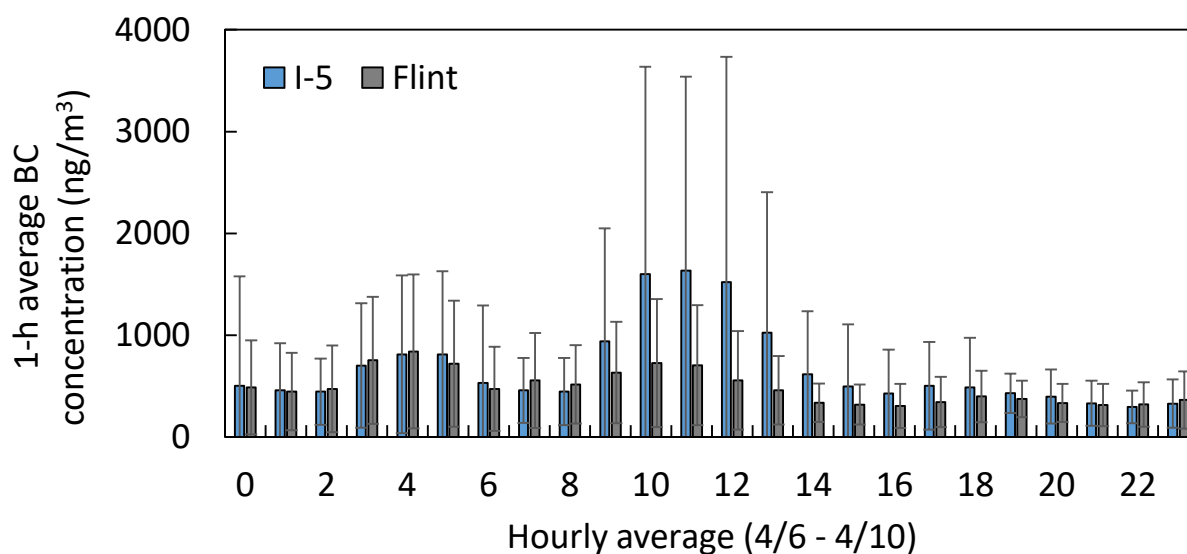


Figure 15. Hourly averages across period of 4/6-4/10 factor of 2 lower, averaged across all days.



It is illustrative to focus the comparison between Flint and I-5 BC levels on only those days that would correspond to occupancy of the school and at times typical of school operation. Therefore, we further focus the data presented on BC levels in these two locations in Figure 16 to target only weekdays and the time period of 7 AM – 4 PM. As shown in Figure 16, as traffic intensity increases on I-5, substantially elevated levels of BC are observed on the I-5 face of the building. Levels on the I-5 building face are nearly a factor of 3 higher than the hourly average observed on the Flint face of the building. This factor is roughly consistent with prior observations of BC “decay” with increasing distance from a freeway. In this case, the I-5 monitoring location is approximately 20 m from the freeway while the Flint Ave monitoring location is approximately 60 m. Prior literature indicates this distance would yield a factor of 2-3 times decrement in BC levels (Zhu et al. 2002; Karner, Eisinger, and Niemeier 2010).

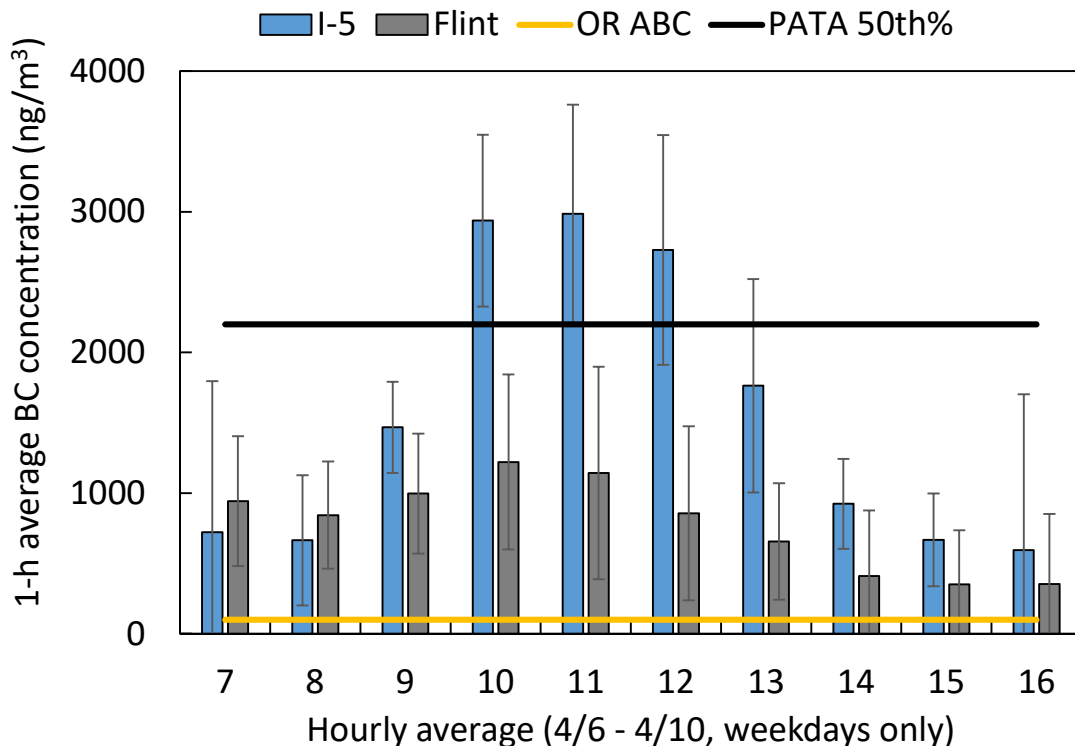


Figure 16. Hourly averages of BC concentrations at the I-5 and Flint Ave. faces of the building for only those days (weekdays) and times (7 AM – 4 PM) corresponding to expected normal daily occupancy at Harriet Tubman Middle School. PATA = Portland Air Toxics Assessment 50th percentile value for monitoring of BC at SE Lafayette Air Monitoring Station in Portland, OR.

To provide context to these measurements of BC, the Oregon Ambient Benchmark Concentration for black carbon is also shown in Figure 16 as is the Portland Air Toxics Assessment 50th percentile value for



annual monitoring of black carbon at SE Lafayette station in Portland, OR. These two lines, corresponding with 100 ng/m³ and 2,200 ng/m³ show that levels recorded at HTMS during normal school periods are bracketed by these values. While Portland, OR is in general elevated with respect to the Ambient Benchmark Concentration for black carbon, there are several hour-long periods where I-5 is elevated above the comparison metric for Portland's urban background while the Flint Ave. face of the building remains below. **These data demonstrate the value of designing the outdoor air ventilation intake of the HVAC system to intentionally draw outdoor air from a location as far away from the freeway as possible. Preferential siting of outdoor air ventilation away from the freeway would result in: 1) cleaner outdoor air, resulting in lower levels of air pollution indoors regardless of HVAC system efficiency, 2) reduced maintenance required for air cleaning systems, and 3) increased resilience with respect to indoor air quality in case of an HVAC system or air cleaning subsystem failure.**

3.6.2 Oxides of nitrogen (NO and NO₂)

Oxides of nitrogen (NO and NO₂, or NO_x) are poisonous, highly reactive gases that form when fuel is burned at high temperatures. They are mainly emitted by automobiles and trucks but also by power plants, industrial boilers, cement kilns, and turbines. During the month of October 2009, ODEQ co-located a nitrogen oxide analyzer at Tubman MS alongside the samplers for the 2009 Tubman MS EPA School Air Toxics Project. Results of that project were summarized previously in the proposal to PPS and showed that the freeway was a strong source of oxides of nitrogen to the site, particularly when the wind is oriented from the west.

Chemiluminescent NO_x monitors were deployed to the Flint and I-5 faces of the building for a four-day period. Due to impacts at the site from construction and renovation activities, only April 9th is available for a weekday comparison of NO and NO₂ levels. A comparison of NO₂ levels between Flint and I-5 deployed monitors is shown in Figure 17 and a comparison of NO levels is shown in Figure 18.

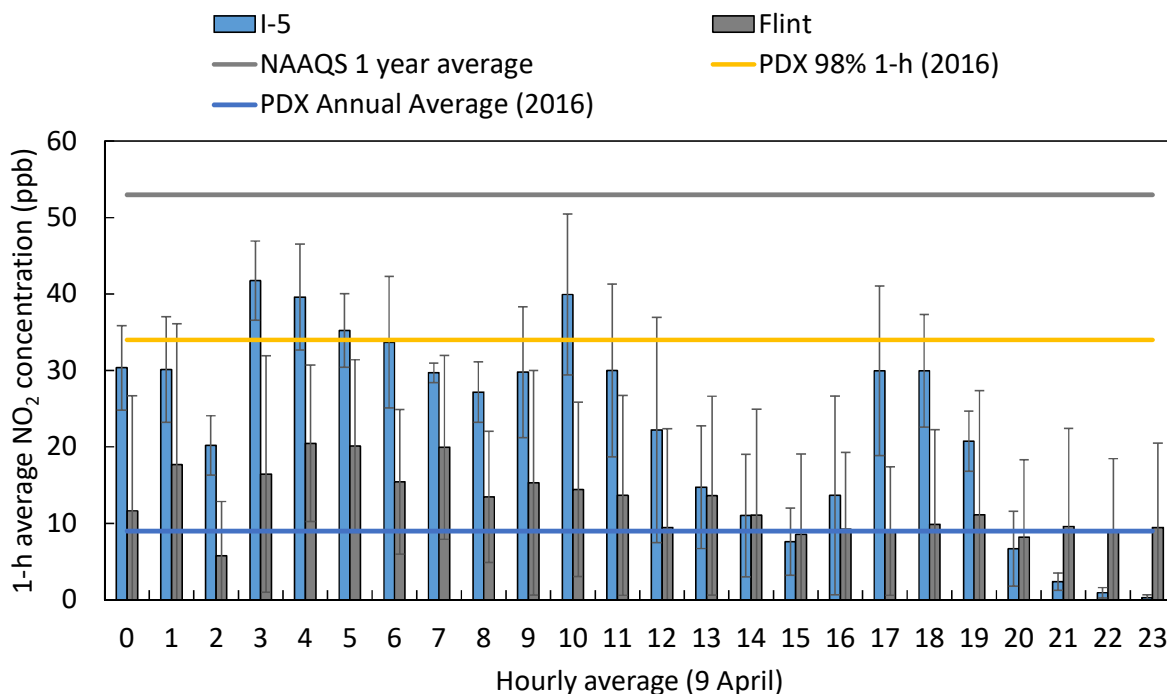


Figure 17. Summary of hourly average NO₂ levels at Harriet Tubman Middle School

As can be observed from Figure 17, NO₂ levels facing I-5 are consistently elevated, particularly during periods of higher traffic intensity in the early AM and evenings. Nitrogen dioxide (NO₂) can be compared to the National Ambient Air Quality Standards, which stipulate that NO₂ should not exceed 53 ppb on an annual average basis. Both sites are well below this national air quality guideline. When comparing with metrics relevant to that of urban background, it becomes apparent that I-5 is impacting this site relative to the urban background levels of NO₂ in the City of Portland. The 2016 annual average NO₂ level reported by the Oregon Department of Environmental Quality at the Lafayette monitoring station in SE Portland is 9 ppb. Note that monitoring sites that report air quality parameters for regulatory compliance are, by design, intended to minimize the influence of local sources like roadways and instead target monitoring the urban/regional background concentrations. The I-5 face of HTMS is consistently elevated above this urban background level while the Flint Ave face of HTMS approaches this value during periods of lower traffic intensity and is below 9 ppb during the late evening period. During the early morning, the I-5 face of the building is more consistent with elevated urban background; the yellow line shown in Figure 17 reports the 98th percentile reporting value of 1-h NO₂ concentrations from 2016 (34 ppb). This value would be indicative of the upper limit of urban background NO₂ levels experienced in the City of Portland.



The diurnal trend of NO levels on April 9th shows a similar trend to that of NO₂. Levels elevated at both I-5 and Flint during periods consistent with morning traffic and levels on the I-5 face of the building and more substantially elevated. There are no regulatory limits on NO and therefore no readily available city-wide regulatory data to provide contextual comparisons to urban background.

These findings are consistent with the spatial assessment of NO₂ (Figure 9) that showed significantly lower NO₂ levels on the Flint side of HTMS.

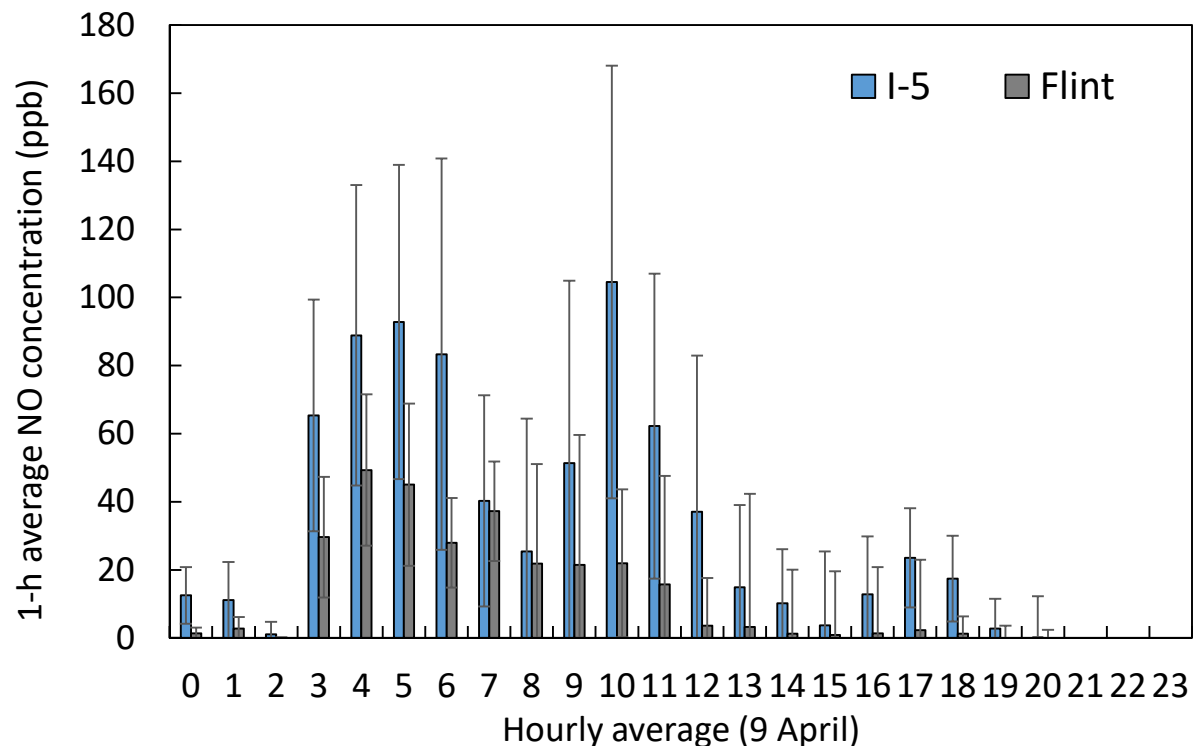


Figure 18. Summary of hourly average NO levels at Harriet Tubman Middle School

The NO and NO₂ data further demonstrate the value of designing the outdoor air ventilation intake of the HVAC system to intentionally intake outdoor air from as far away from the freeway as possible.

3.7 Summary of HVAC recommendations to date

In institutional buildings like Tubman Middle School, in-duct HVAC air cleaning and filtration are options for improving indoor air quality and/or reducing rates of outdoor air ventilation. Both outcomes could, theoretically, improve indoor air quality, depending on indoor emissions of air pollution, indoor sinks of air pollution, and outdoor levels of air pollutants. Technologies exist that are designed to reduce both the indoor particle levels as well as levels of indoor gaseous contaminants; generally, distinct media



are necessary to capture air pollutants in each of these two broad classes of contaminants. The two most well-established approaches for cleaning indoor air are mechanical filtration and sorbent air cleaners.

Mechanical filters employ porous media, where particles entrained in air flowing through the filter are attached to the filter and removed from air. Electronic particle and electrostatic-based air cleaners can also be used to remove particles from air; these systems can be effective, but both present concerns for byproduct formation, specifically O₃ from corona discharges used to charge particles. It is worth noting that any system intentionally introducing O₃ into the air supply or indoor space under the guise of improving indoor air quality should be unequivocally avoided (OAR US EPA 2014).

3.7.1 Options for removal of particle-phase air pollutants

Particle filtration has been shown to reduce indoor PM, including PM_{2.5}, PM₁₀, and black carbon by 41-97% in institutional buildings (McCarthy et al. 2013; Polidori et al. 2013). In general, filters should be selected considering their known efficiency at removing particles as a function of particle size. A summary of the removal efficiency as determined by the Minimum Efficiency Reporting Value (MERV) defined by ASHRAE is shown in Figure 19.

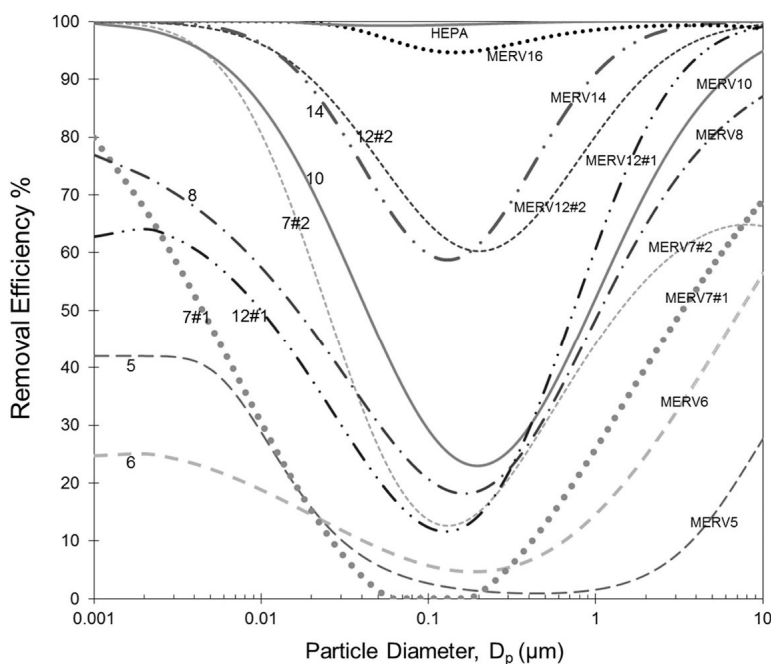


Figure 19. Summary of particle removal efficiency as a function of MERV rating. Figure taken from Azimi, Zhao, and Stephens (2014).



Section 2.1 outlined a range of potential concerns associated with elevated concentrations of particles across size ranges that include UFP ($<0.1 \mu\text{m}$), particle associated metals (predominantly occurring at diameters $< 0.8 \mu\text{m}$ and $> 6.7 \mu\text{m}$), and black carbon ($\sim 60 \text{ nm}$ mode for particle number or $1 \mu\text{m}$ mode for particle mass) in addition to the more well-known particulate matter classifications of PM_{2.5} (all particles with diameter less than $2.5 \mu\text{m}$) and PM₁₀. Thus, it is anticipated that the HVAC system should specify a high-MERV rating filter to treat for the broad range of particle sizes that are likely to be elevated due to proximity to the freeway. Given the size ranges of PM pollutants expected to be elevated near a freeway, **it is recommended that a minimum of MERV 16 filtration be employed in the treatment of outdoor ventilation air to reduce levels of ultrafine, fine, accumulation, and coarse mode particulate matter expected and observed to be elevated at the HTMS site.** A figure showing a typical particle size distribution observed at HTMS is shown in Figure 21.

3.7.2 Options for removal of gas-phase air pollutants

Sorbent air cleaners use physical adsorption and/or chemisorption to remove gaseous contaminants from air streams. The most common adsorbent is activated carbon which can effectively remove a relatively broad range of gas-phase contaminants, including many VOCs and ozone. Other adsorbents include activated alumina, zeolites, and molecular sieves that are tailored to specific contaminants. Some adsorbents are doped with additives which cause irreversible reactions to occur on sorbent surfaces, further expanding the range of potential chemicals that can be targeted by air cleaning sorbents. In general, a single sorbent media is not generally sufficient to treat multiple contaminants, and thus a range of chemical and physical sorbents are required to be specified for the particular contaminants of concern.

Importantly, as summarized by ASHRAE position statements, the scientific literature indicates that there is only significant evidence that suggests health benefits from porous media particle filtration systems (ASHRAE 2015). However, the summary statement also notes that there is evidence that sorbent air cleaners can reduce indoor concentrations of gaseous contaminants, but that health studies directly linking these reductions to improvements in health are presently lacking (ASHRAE 2015). Literature suggests that activated carbon and mechanical filters are effective at removing indoor air pollutants derived from vehicle emissions. One study showed that activated carbon air cleaning along with ventilation reductions can reduce indoor VOC concentrations by 60-80% (Sidheswaran et al. 2012). Indoor air quality can be improved by using coconut shell activated carbon filter: this kind of filter can decrease the concentration



of most VOCs and also ozone concentrations. The theoretical saturation time of the filter exposed to the VOC concentrations was estimated to range between 247 and 873 days (depending on the activated carbon pellet diameter and VOC concentration) (Gallego et al. 2013).

Other air cleaning technologies exist, including photocatalytic oxidation systems, where redox reactions are initiated by light and occur on a semiconductor or catalyst material. These systems offer advantages of relatively low pressure drops, wide variety of target compounds treated, and long life cycles. Downsides include energy costs, maintenance costs, and byproduct formation. Byproducts potentially include incomplete degradation products and/or ozone generated from irradiation of O₂ if light wavelengths and intensities are not carefully selected. Other systems present in the market include UV disinfection systems, which target microbial contaminants not likely to be a concern from freeway exhaust

As noted previously, gas-phase VOCs may constitute thousands of potential VOCs with knowledge of specific compounds or classes of compounds informing an HVAC design. For example, polar VOCs may require distinct treatment processes from non-polar VOCs and may breakthrough over different time periods that would require a particular sorbent changeout schedule. At this stage, **it is recommended that a system be designed conservatively with respect to possible VOC contaminants. We recommend that manufacturer specifications for minimum air-media contact times or greater be ensured in the HVAC design. Ideally, multiple (2-3) media bed housings would be installed in the HVAC system to afford the opportunity to select specific sorbents targeting classes of gas-phase compounds while maintaining manufacturer recommended air-media contact times.**

The sorbents identified for use in the system will include a broad spectrum activated carbon mixed in some proportion with an activated alumina/potassium permanganate impregnated sorbent. This combination will be finalized through further discussion with various sorbent vendors; however, the nature of the media with respect to the design of the HVAC system (i.e., sorbent impact on airflow-pressure relationships) should not be impacted. The selection of the sorbent blend will impact only the chemical characteristics of the sorbent and therefore which compounds it targets. It is important to note that manufacturer information is limited in determining the optimal sorbent. Sorbent manufacturers provide removal efficiencies and capacities for controlled laboratory conditions; the performance of a sorbent in a real environment where it is challenged with a complex mixture of particle and gas-phase pollutants may alter its removal capability. Therefore, **we recommend that periodic (quarterly) monitoring of VOCs and gas-phase pollutants downstream of the air cleaning system be performed**



to confirm performance of the system with respect to removal efficiency and capacity. At a minimum, this monitoring should include sampling for VOCs expected to be elevated due to vehicle combustion (benzene, toluene, ethylbenzene, and xylenes, as well as other VOCs) and oxides of nitrogen.

To reiterate the conclusion of the I-5 vs. Flint monitoring: **the outdoor air ventilation intake of the HVAC system should be designed to preferentially intake outdoor air from as far away from the freeway as possible.** Given that the monitoring on Flint Ave occurred on the SE corner of the building which is closest to the freeway, **it is likely that any location on the Flint face of the structure would be preferable with respect to air quality compared to the I-5 face of the building.** The reasons for the preference are: 1) outdoor air quality would be improved, resulting in lower levels indoors regardless of HVAC system efficiency, 2) reduced maintenance on air cleaning systems, and 3) increased resilience with respect to indoor air quality in case of an HVAC system or air cleaning subsystem failure.

3.7.3 Estimation of removal efficiencies in HVAC system

3.7.3.1 *Present understanding of HVAC air cleaning operation*

The following section summarizes the anticipated removal efficiencies of the HVAC system that incorporates three stages of air cleaning: a MERV (minimum efficiency reporting value, as defined by ASHRAE in Standard 52.2) 8 pre-filter, a MERV 16 or HEPA filter, and a sorbent media bed. The three stages are shown in Figure 20. Note that the order of these devices is intentional: the pre-filter serves as a preliminary stage of initial particulate matter removal that will lengthen the lifespan of the more expensive MERV 16 filter. Second, it is recommended that the gas-phase air cleaning media (i.e., the sorbent bed), be placed downstream of both the MERV 8 and MERV 16 filter. This will serve to prevent fouling of the sorbent media with particulate matter that will effectively shorten its lifespan.

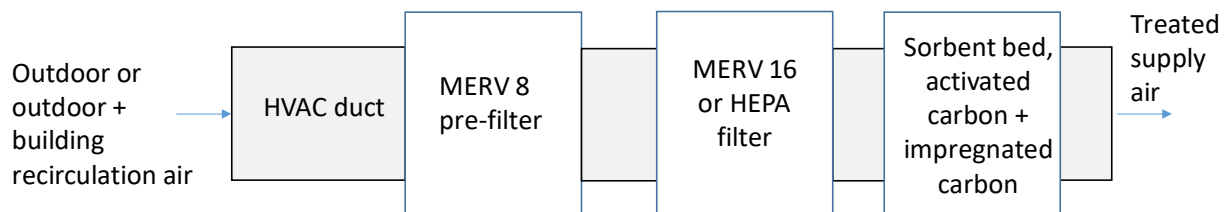


Figure 20. Summary of preliminary proposed air treatment processes to be installed in the HVAC system of Harriet Tubman Middle School. MERV = minimum efficiency reporting value, HEPA = high efficiency particulate air.



Preliminary discussions with several vendors of gas-phase air cleaning media have informed the early stage design of this component of the system. Approximately 96 lbs of air cleaning media installed in 24 modules achieves an air-media contact time of 0.1 seconds recommended by a manufacturer of air cleaning media. Distinct media are required to target different classes of gas-phase compounds based on their behavior (e.g., polar volatile organic compounds may require different sorbents than non-polar volatile organic compounds). **Ideally, the sorbent bed would be separated into 2-3 independent beds to provide maximum flexibility for targeting different compounds with full 0.1 second contact times for each media.** However, a compromise would be to create a custom blend of two or more different sorbents placed in one stage, acknowledging the potential for a trade-off in contact time for each of the two sorbents. The subsequent analysis of air cleaning efficiencies assumes a 0.1 second contact time is achieved for all compounds. This assumption is valid for the subsequent analysis as manufacturer data indicates a single sorbent can effectively remove benzene, toluene, ethylbenzene, and xylenes (BTEX) and NO₂ with at least 98% efficiency.

3.7.3.2 *Particulate matter size distributions*

A central goal of the monitoring campaign conducted in Phase I was to obtain size-resolved time-series data characterizing the particulate matter levels in outdoor air at HTMS. This information serves to inform two goals. First, size of particulate matter has been shown to be a key determinant of health impact as the effective diameter of a particle governs its surface area which has shown to elicit inflammatory responses and oxidative damage in the respiratory system (Valavanidis, Fiotakis, and Vlachogianni 2008). Second, as described previously in Section 3.7.1, the size of the particle is a controlling parameter that governs its removal via filtration (Fisk W. J. et al. 2002).

The particle size distribution can be presented in several different ways, each with a distinct goal. The interested reader is referred to the seminal text *Aerosol Technology* for detailed explanations of the practices employed in presenting these data (Hinds 1999). Very briefly, particle size distributions are typically presented in terms of the particle number, particle surface area, particle volume, or particle mass. Generally, particles are assumed to behave as that of a sphere, and so the particle diameter is a metric that can be used to convert amongst these various metrics.

In Figure 21, we report the particle size distribution by the number of particles present in “bins” of the particle sizes transformed by the natural logarithm. This procedure enables better visualizations as the particle size distribution is non-linear across order of magnitude ranging from <10 nanometers to > 10 micrometers. Put simply, the particle number distribution (blue line) emphasizes a visualization of the small particles (<100 nm) that are great in number, but contribute relatively little in terms of volume. On



the other hand, the particle volume distribution (black line), is related to the blue line by the cube of the particle diameter. Therefore, larger particles contribute more substantially to this visualization of the particle size distribution. The volume of particles presented in the black line is directly proportional to the mass of particles assuming the density of particles are known.

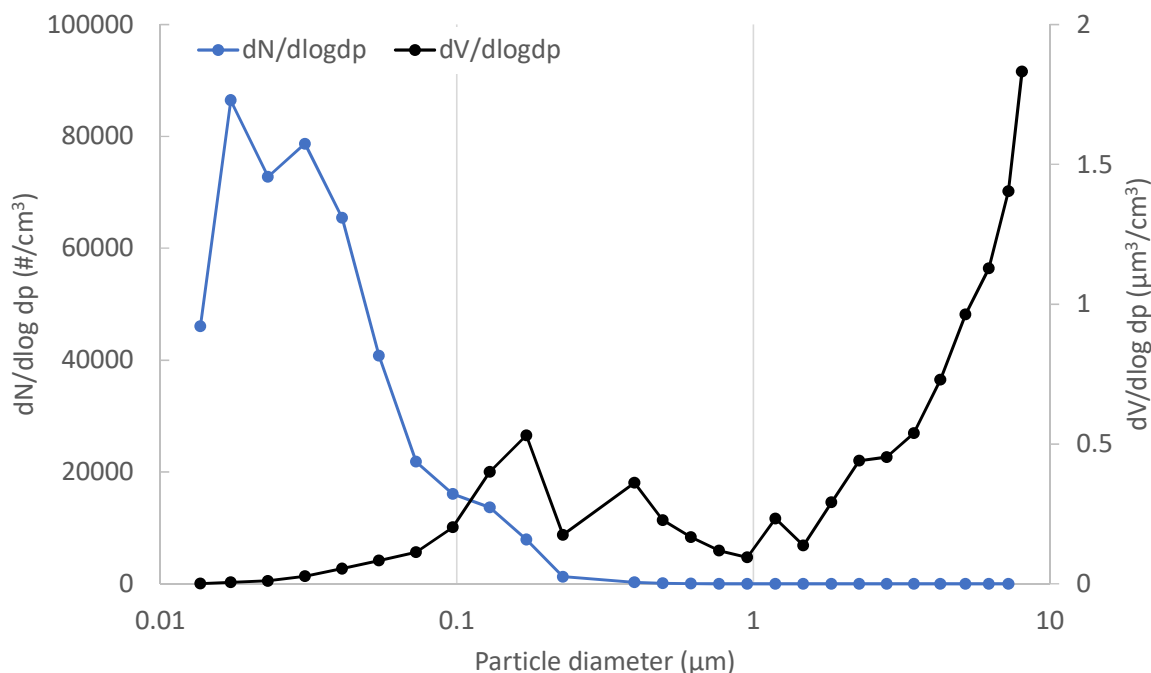


Figure 21. Particle size distributions by number and by volume. Distributions are the average across all weekdays during the time period of typical school occupancy, 7 AM – 4 PM. Data were collected from the period of March 13 – March 29, 2018. All data collected from the main monitoring site facing I-5 (the “greenhouse”).

The central conclusion from this summary of the collected particulate matter size distribution data is that elevated levels of particulate matter are present across a broad range of particle diameters. Thus, it is recommended that a MERV 16 or HEPA filter be employed to ensure control of particles ranging from < 10 nanometers to > 10 micrometers is in place in the HVAC system.

The efficiency of removal of particles (by number) of a MERV16 filter in the HVAC system was evaluated for the particle size distributions presented and compared to that of a MERV 8 filter alone for comparison. In Figure 22, the comparison is made for particle number emphasizing the presence of very small particles in the ultrafine range that may be damaging to human health (N. Li et al. 2003; HEI 2013; Tobías et al. 2018).

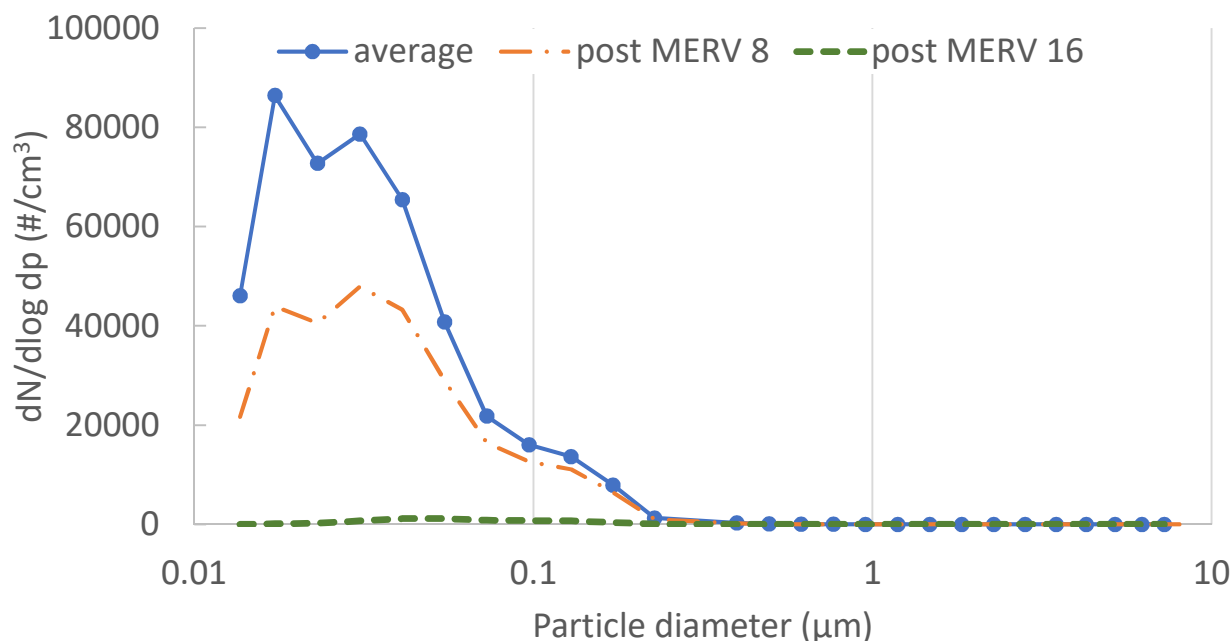


Figure 22. Modeled removal of particles (by number) across a MERV 8 and MERV 16 filter using the average particle size distributions determined for Harriet Tubman Middle School during school days and school hours from March 13-29, 2018. Removal efficiencies are taken from the models presented by Azimi, Zhao and Stephens (2014).

Note that the MERV 16 filter (green line) is capable of very high removal of particles in downstream air when evaluated by particle number while the MERV 8 filter leaves a substantial number of particles present in downstream air. **Note that these concentrations downstream of the filter are not necessarily the same concentrations that would be present in indoor air.** This concept will be further discussed in Section 3.7.3.6

The efficiency of removal of particles (by volume) of a MERV16 filter in the HVAC system was evaluated for the particle size distributions presented and compared to that of a MERV 8 filter alone for comparison. In Figure 23, the comparison is made for particle volume, emphasizing the presence of larger particles in the fine and coarse modes.

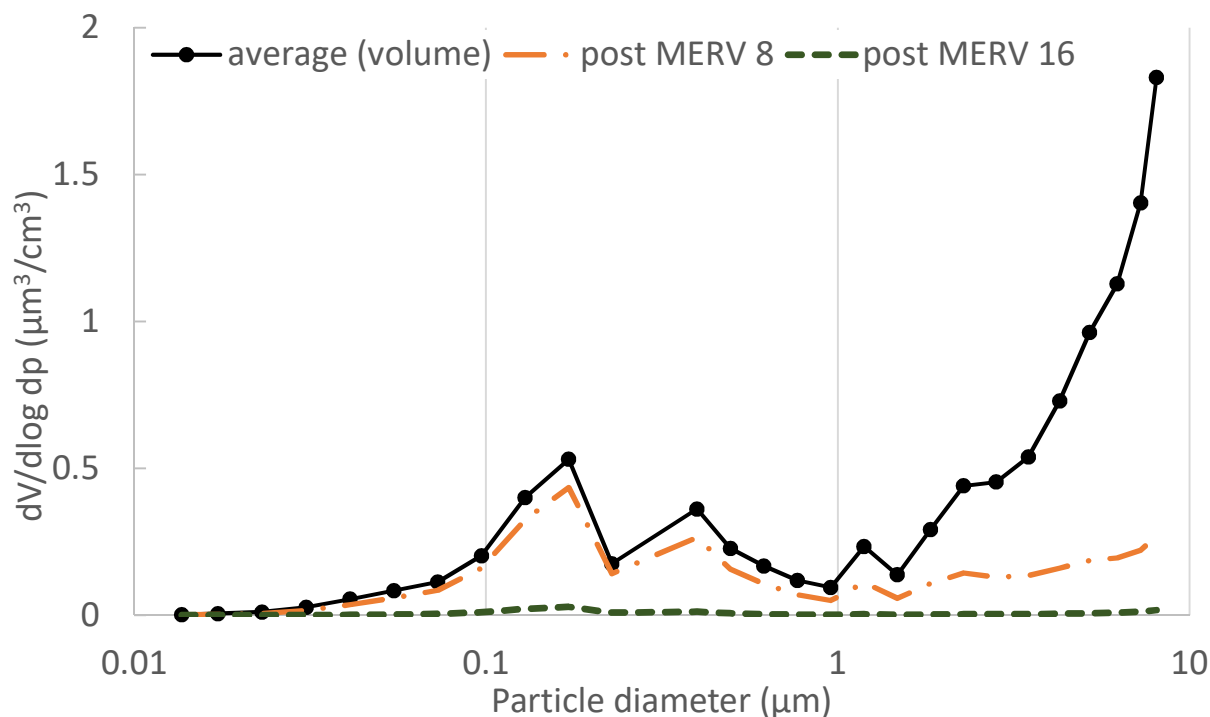


Figure 23. Modeled removal of particles (by volume) across a MERV 8 and MERV 16 filter using the average particle size distributions determined for Harriet Tubman Middle School during school days and school hours from March 13-29, 2018. Removal efficiencies are taken from the models presented by Azimi, Zhao and Stephens (2014).

Note that the MERV 16 filter (green line) is capable of very high removal of particles in downstream when evaluated by particle volume while the MERV 8 filter leaves a substantial volume of particles present in downstream air. **Note that these concentrations downstream of the filter are not necessarily the same concentrations that would be present in indoor air.**

The volume distribution presented in Figure 23 is dimensionally equivalent to that of $\mu\text{g}/\text{m}^3$ assume particle density and shape factor corrections of unity. We summarized all particle bins $2.5\ \mu\text{m}$ and less collected from the optical particle sizer and scanning mobility particle sizer to estimate the volume concentration of $\text{PM}_{2.5}$. This analysis provides an approximation of the more familiar mass-based $\text{PM}_{2.5}$ metric in units of $\mu\text{g}/\text{m}^3$, again, assuming that a particle density and shape factor correction are known. Gravimetric PM measurements are available to make these corrections, and appear roughly consistent with the volumetric measurements reported here (see Section 6.1 for the gravimetric PM measurements made at the Harriet Tubman site). Shown is Figure 24 is the removal effectiveness of a MERV 16 filter for removing $\text{PM}_{2.5}$ from the outdoor ventilation air entering the building via the HVAC system. For the



purposes of this analysis, the removal effectiveness of the HVAC system would scale accordingly with the density and shape factor correction; nevertheless, a MERV 16 filter is highly efficient at removing PM_{2.5} and would reduce levels downstream the filter to very low levels regardless of these corrections.

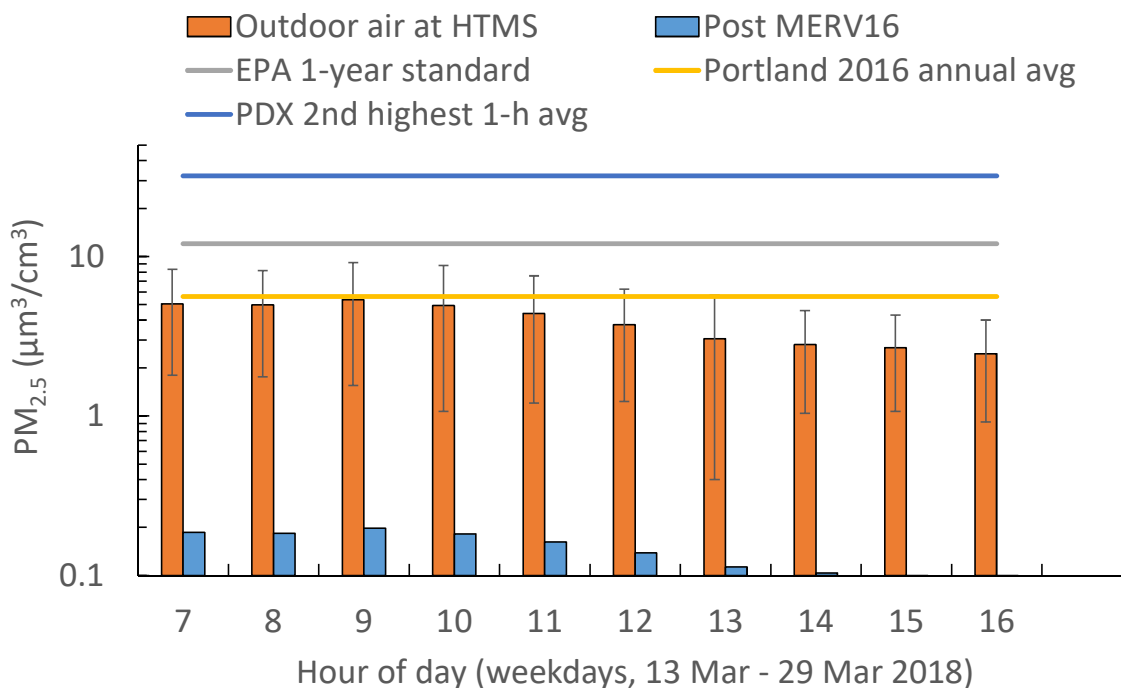


Figure 24. Hourly average PM_{2.5} levels at HTMS and predicted levels of PM_{2.5} downstream a MERV 16 filter. These values are compared to the EPA NAAQS standard, the 2016 annual average level in Portland, OR (determined from SE Lafayette monitoring station) and the 2nd highest 1-h average in Portland (again determined from SE Lafayette monitoring station).

3.7.3.3 Nitrogen dioxide removal by HVAC system

Nitrogen dioxide is also expected to be removed by the sorbent media. Figure 25 shows the monitoring results for NO₂ for a two day period, 21-23 March, 2018. The data is averaged to include only those time periods where the school is expected to be typically occupied (7 AM – 4 PM). For reference, the monitoring data is compared to the U.S. EPA NAAQS for NO₂ of 53 ppm and the PDX annual average of 9 ppb (SE Lafayette monitoring station). Finally, the site data is compared to the 98th percentile value for central Portland (SE Lafayette monitoring station)

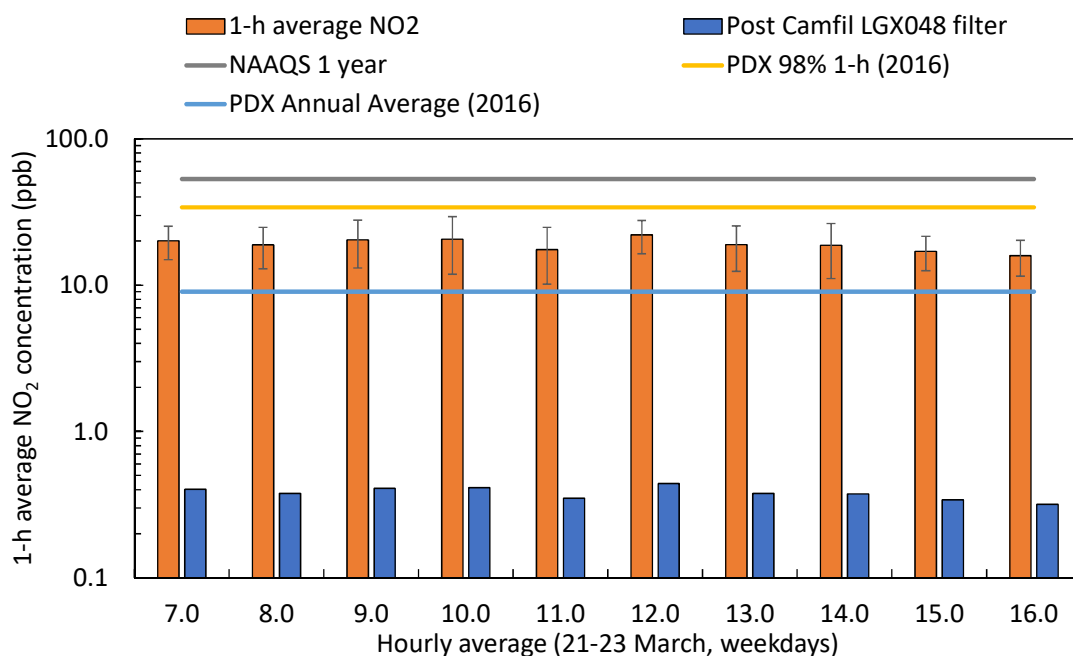


Figure 25. Hourly average NO₂ levels at HTMS and predicted levels of PM_{2.5} downstream a MERV 16 filter. These values are compared to the EPA NAAQS standard, the 2016 annual average level in Portland, OR (determined from SE Lafayette monitoring station) and the 2nd highest 1-h average in Portland (again determined from SE Lafayette monitoring station).

Note that the removal by the sorbent media (LGX048, Camfil) is projected to be highly effective at removing NO₂ from the outdoor ventilation air. To achieve these removal efficiencies, it would be necessary to maintain, at a minimum, a 0.1 second contact time between the air and the sorbent media. This design constraint can be achieved by varying the quantity of sorbent media present and/or the amount of air treated by a given mass of media until this contact time is achieved.

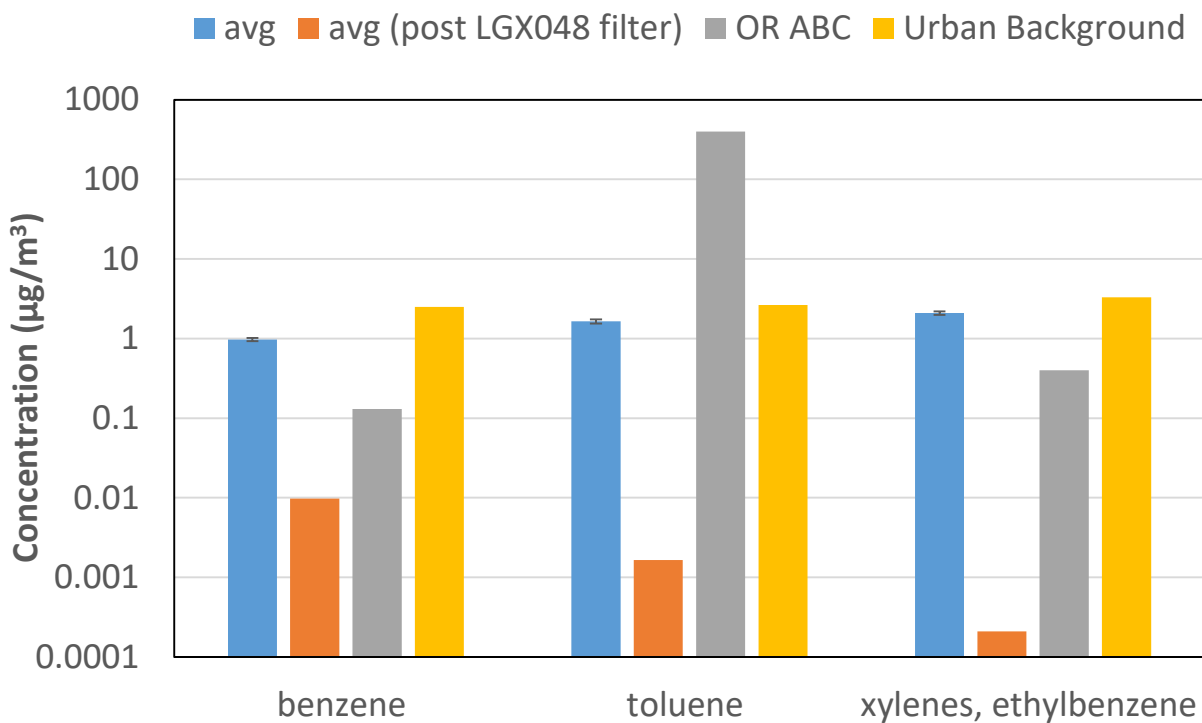
3.7.3.4 VOCs (*benzene, toluene, ethylbenzene, xylenes*)

Volatile organic compounds are also expected to be removed by the sorbent media. Figure 26 shows the monitoring results for three selected VOCs/group of VOCs. Outdoor concentrations of VOCs are calculated from data collected by the proton transfer reaction – time of flight – mass spectrometer for periods when HTMS would be typically occupied by students (7 AM – 4 PM). The three selected VOCs are included in the metric BTEX (benzene, toluene, ethylbenzene, and xylenes); BTEX is well-known to be associated with freeway exhaust (Raysoni et al. 2017; R. Li et al. 2017). Since these compounds were monitored with the PTR-TOF-MS, the structural isomers of the xylenes and ethylbenzenes could not be separated and are reported as the sum of *m*-xylene, *o*-xylene, *p*-xylene and ethylbenzene. The sorbent



manufacturer reports that all four of these compounds can be removed with >99% efficiency if a 0.1 second contact time is maintained.

For reference, the monitoring data is compared to Oregon Ambient Benchmark Concentrations and the monitored urban background concentrations reported in the Portland Air Toxics Assessment (2004) performed by ICF consulting. Note that outdoor levels are in exceedance of OR ABC's for benzene and possibly for xylenes and ethylbenzene from this PATA 2004 report. However, urban background of these compounds is variable – note that lower levels were observed in recent monitoring conducted at the Humboldt School by Oregon DEQ and reported in Section 3.1. The OR ABC for xylenes is $700 \mu\text{g}/\text{m}^3$ while the ABC for ethylbenzene is $0.4 \mu\text{g}/\text{m}^3$. Refer to Section 3.1 for a more in-depth investigation of ABC comparisons of gas-phase compounds that summarizes the two approaches to monitoring VOCs used in this investigation (PTR-TOF-MS and TD-GC-MS).



Pollutant, average of weekdays from 7 AM - 4 PM, 12-25 March

Figure 26. Summary of expected air pollutant concentrations downstream the sorbent media in the HVAC system. Comparisons provided for urban background are derived from the 2004 Portland Air Toxics Assessment. OR ABC is the Oregon Ambient Benchmark Concentration.



With regard to removal, the sorbent media (LGX048, Camfil) is projected to be highly effective at removing these selected VOCs from the outdoor ventilation air. To achieve these removal efficiencies, it would be necessary to maintain, at a minimum, a 0.1 second contact time between the air and the sorbent media.

3.7.3.5 Compounds not anticipated to be removed by the HVAC system

A well-designed HVAC system can improve air quality in many, but not all respects. Several monitored compounds are not expected to be removed by the HVAC system. For example, carbon monoxide and nitric oxide are not effectively removed by fibrous filter media or the sorbents typically available for air treatment. These compounds generally require oxidation processes that would convert the compounds to harmless compounds (e.g., oxidation of CO to CO₂) or to compounds that can be treated via other removal mechanisms (e.g., oxidation of NO to NO₂) (Selby and Counce 1988; Kolobov et al. 2017).

While the HVAC system cannot remove all air pollutants, it can serve to reduce many of the air pollutants of concern, including those air pollutants associated with particles as well as a broad range of organic compounds. Given that exposures to complex mixtures of air pollutants is an emerging area of air pollution and toxicology with many unknowns (Mauderly and Samet 2009), the HVAC system is likely to contribute to reductions in exposures to individual air pollutants that are known to adversely impact human health as well as reduce many of the components of the complex mixture of air pollutants included in freeway emissions that have been, as a whole, implicated in a large body of research demonstrating health effects associated with exposure to air pollution from vehicle emissions (Brugge, Durant, and Rioux 2007).

3.7.3.6 Building ventilation and infiltration and indoor air quality

The HVAC system is a key component to maintaining good indoor air quality at HTMS. However, it is essential that the building be considered holistically with respect to outdoor air quality concerns at the site. Outdoor air typically enters buildings via three mechanisms: mechanical ventilation, natural ventilation, or infiltration. Mechanical ventilation is typically the most straightforward to assess for a building, as it relies on mechanical systems that are well characterized and consistent. Natural ventilation and infiltration both rely on pressure differentials created across openings in the building envelope (enclosure) that serve as a driving force to cause exchange of indoor air for outdoor air. For HTMS, natural ventilation, where openings are specifically designed for provision of outdoor air via large apertures like windows, louvers, and doors should not be considered for HTMS. Infiltration is a

mechanism whereby outdoor air migrates across deficiencies in the building envelope and enters the indoor environment (see Figure 27). Infiltration will result in “short-circuiting” of the HVAC system, allowing outdoor air that is not treated by the air cleaning systems in the HVAC system to enter the building.

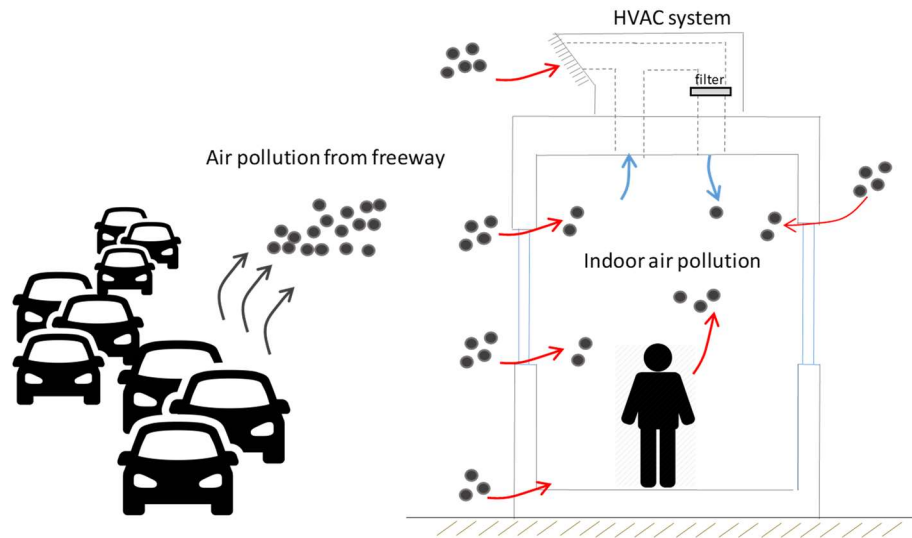


Figure 27. Potential pathways of outdoor air pollution entering a built environment.

Infiltration is driven by pressure differentials that are created between an outdoor environment and an indoor environment, induced by wind, temperature differences (stack effect), or unbalanced mechanical systems. Students at HTMS would be best protected from outdoor air pollutants if the building, or at a minimum, the face of the building adjacent to I-5, were operated at a slight positive pressure. In addition, the building shell facing I-5 should be weatherized to be made airtight and the renovation should limit window-opening on the I-5 side of the building to only emergency events. A building commissioning effort post-renovation should include balancing of the HVAC system to ensure that airflows do not result in pressures that contribute to outdoor air bypass of the HVAC system.

3.8 Outdoor air mitigation and site fluid mechanics

Urban forests are often proposed as a means of ameliorating air pollution in cities. While studies that investigate the city-scale indicate generally positive effects of urban vegetation on air quality (Yang, Yu, and Gong 2008), local effects of barriers (often vegetation, but also abiotic structures like sound walls) are mixed in terms of mitigation benefit in the research literature. For example, recent studies have come to conclusions that show street level vegetation as increasing (Vos et al. 2013; Wania et al. 2012) or decreasing (Abhijith and Gokhale 2015; Pugh et al. 2012) local concentrations of air pollutants. The Environmental Protection Agency promulgates a summary of recommendations for the use of roadside



vegetation barriers to improve near-road air quality, noting that “studies have shown that noise and vegetative barriers can reduce downwind pollutant concentrations near roads” and offer recommendations for constructing roadside barriers to optimize the downwind reduction in air pollution emitted to vehicular traffic (ORD US EPA 2016).

Studies of the impact of urban vegetation are carried out from fundamental as well as applied perspectives. Urban forests were incorporated in Beijing, Los Angeles, Sacramento and Salt Lake City, and showing a direct impact in decreasing local pollution as shown by Yang et al. (2005), Akbari (2002) and Coder (2016). On the side of noise, strategies have been proposed in a careful implementation by considering parametric studies of tree placement, foliage, density of trees, and orientation depending on the source. Examples of these observations are found in Kragh (1981), Aylor (1972), and more recently in Fang & Ling (2003) and Maleki & Hosseini (2011). Such strategies can be considered in the proposed work. In addition, Cal has recently been funded to work on non-homogeneous forest canopies with aim to understand weather forecasting and deforestation. Of relevance, strategies integrated in different studies (summarized by Janhäll, 2015) have yielded a percentage decrease in PMs on the order of 40%; approaches in the proposed study could improve upon these. Within this review, works pointing towards the possible strategies and improvements specifically in areas where roadsides are present. With at least a dozen publications with authors in common, these date back to mid-2000 and as late as 2017 by Fuller et al. (2017), which specifically deals with concentration on a school campus. Perhaps the most relevant, Hagler et al. (2012), provide comparisons of various barrier composed of trees or brick. Benefits were achieved yet were site and wind condition dependent.

In considering an even more recent review, Abhijith et al. (2017) evaluates a more comprehensive set of conditions both in the field and wind tunnel settings. As concisely stated in the abstract: *“For open road conditions, wide, low porosity and tall vegetation leads to downwind pollutant reductions while gaps and high porosity vegetation could lead to no improvement or even deteriorated air quality. The review considers that generic recommendations can be provided for vegetation barriers in open road conditions.”* Remediation via vegetation is systematically discussed in Baldauf (2017) where comments on height, porosity, thickness, length and coverage are within the parameter space when considering its design and implementation. Solid barriers are reviewed in an article, Gallagher et al. (2015), reaching similar conclusions to that by Abhijith et al. (2017): *“Measurement studies and modelling investigations have found relatively consistent reductions in pollutant concentrations downwind of the barriers. However, similar to the roadside vegetation studies, an increase in upwind concentrations has been identified due to the recirculation of pollutants in the zone in front of the structure. ...reattachment of a*

plume downwind of a barrier could lead to higher concentrations further downwind of the barrier compared to no barrier under some settings. The height and layout of the noise barrier... presented the greatest influence on the dispersion of pollutants along the highway.” Indeed, this should be deemed as relevant here in this study. It is noted that numerous studies are consulted when crafting these reviews for which further detail and information may be extracted.

3.8.1 Model Design and Manufacturing

The key parameters informing the design of the model used in this study are the mean wind direction and an appropriate length scale. Information regarding the average wind speed and directions is detailed in publicly available NOAA data collected at the Portland Airport from 1950 through 2012. For the months of April through September, the wind faces NW at 330° with an average speed of 3.2 m/s depicted in Figure 28 by arrow A. For other six months of the year, the wind faces SE at 150° with an average speed of 3.9 m/s indicated by arrow B.



Figure 28. Elevation map of the site and surrounding area. Arrow A shows the wind direction for April through September while arrow B shows the wind speed for October through March. The rectangle centered about the school indicates the region of interest for the scale model.

The topography and architecture surrounding the site is represented at a scale of 1:120 for the purposes of this study (Figure 29). A scale of 1:120 was chosen to provide the highest possible resolution in



describing the wind flow surrounding the site with the equipment at the Portland State University (PSU) wind tunnel. Additionally, this scale considers the influence of major obstacles located upstream of the mean wind for each prominent direction.

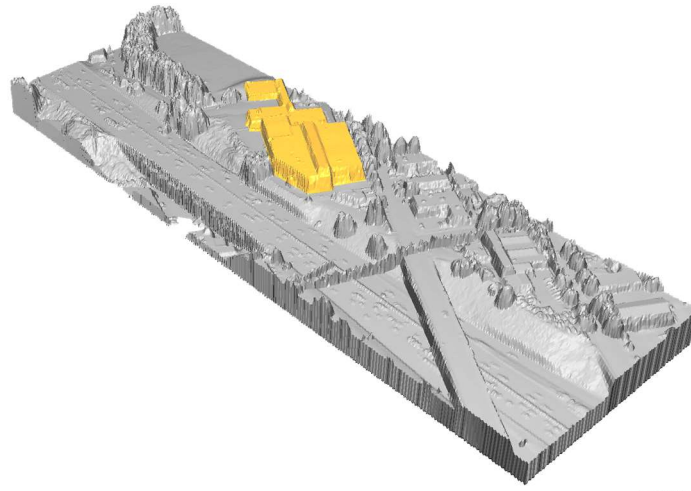


Figure 19. 3D model derived from the DOGAMI LIDAR study. Tubman Middle School shown in yellow.

LIDAR data was acquired from the 2014 Oregon Department of Geology and Mineral Industries (DOGAMI) LIDAR survey for the area of interest depicted in Figure 29. The LIDAR data contains three dimensions of measurement accurate to approximately 1m and is used as the basis for model construction. The LIDAR data was analyzed with GIS software, Geographical Information System (GIS) software and a 3D model was developed as shown in Figure 30. Elevation slices were defined from the 3D model such that each slice represents a 0.5 m change in elevation.



Figure 30. Elevation contours each line represents a 0.5 m elevation change. Topography model is made of layers per the contours.

In the process of creating the model, the elevation slices will be cut out of 4mm thick cardboard and layered to create a scaled physical model of the topography surrounding Tubman Middle School. Upon



aligning layer assembly, the model will be coated with papier-mâché to smooth out any ridges present as a result of the layering method used. Dimensions of the school and its surrounding buildings were also identified via GIS Lidar data and model structures were defined using 3-d modeling software. Models of the school and relevant structures will be separated fabricated and fixed to the topography in their precise locations determined via the LIDAR survey.

The proposed scale model of Harriet Tubman Middle School and relevant surroundings will be situated in the 1.2 m by 0.8 m by 5.0 m wind tunnel at Portland State University. Data collection will be taken via stereo Particle Image Velocimetry (PIV). In this technique, a planar laser sheet is generated to illuminate particles and capture snapshots of these using two high-resolution cameras to produce instantaneous, three-dimensional velocity flow fields within the interrogation area.

The laser sheet plane will be situated perpendicular to the direction of traffic on Interstate 5 and will be aligned central to the school site. The plane width intends to include a portion of the driveway and all of the present hillside on the western edge of the campus as well as a portion of the interstate width. The laser sheet plane height intends to span a scaled distance of 4 m below the main school floor level to 4 m above the tallest point of the building. This orientation will be maintained for all trial cases.

3.8.2 Experimental cases

Experimental topographies will be considered to examine wind flow effects of all relevant and proposed configurations:

-Current topographical configuration

-Freeway expansion only: Western hill removed, No wall/tree separation along freeway, Flint Street overpass as currently present

-Freeway expansion with wall/treeline added: Western hill removed, Wall/tree separation along freeway, Flint street overpass as currently present



4 Conclusions

4.1 Key Findings

This report summarizes the findings and progress to date of this Phase I effort as well as recommendations generated from the Phase I effort. Key findings from the initial air monitoring campaign are that, as anticipated, the site air quality is negatively impacted by its proximity to the freeway. Out data show that there is a gradient of traffic related pollutants that decreases as function of distance away from I-5 N, reaching background levels about 200-300 feet from the freeway. Evidence for this findings includes data derived from passive sampling of nitrogen dioxide in a 1200 ft² area around Tubman Middle School and mobile transects of ultrafine particles around Tubman Middle and Lillis Albina City Park.

We also observed that air sampled on the SW side (freeway side) of Tubman Middle School is heavily impacted by freeway emissions. We observed that air sampled on the Flint Ave. side is also impacted by freeway emissions but pollution is at a lower concentration. Evidence for these conclusions are derived from measurements of coming freeway have elevated levels of black carbon, carbon monoxide, ultrafine particles and nitrogen oxides, that diurnal patterns of elevated air pollutants at the site are consistent with traffic patterns, and simultaneous measurements of tracers on I-5 and Flint Ave. sides of building, The latter data show reduced levels of black carbon and oxides of nitrogen during simultaneous monitoring on the I-5 and Flint Ave. faces of the building.

Many air pollutants measured at Tubman are elevated compared to Portland urban background site (DEQ SE Lafayette). However, criteria pollutants are below National Ambient Air Quality Standard for monitoring period. Toxic metals were below Oregon Ambient Benchmark Concentrations (except for Arsenic). Some toxic volatile organic compounds (acroliein, naphthalene, benzene) were above Ambient Benchmark Concentrations. Evidence for these conclusions is derived from comparison of monitored data with ODEQ urban monitoring site (a site for regulatory use under the NAAQS), comparison of monitored data with Oregon Department for Environmental Quality Humboldt site for VOCs, and comparison of monitored data with Oregon Ambient Benchmark Concentrations.

While the site is negatively impacted with respect to air pollution due to I-5, preliminary modeling shows that air pollutants of concern in HVAC outdoor ventilation air can be reduced to levels substantially below urban background and levels of health concern. Evidence for this conclusions results from



modeling of air cleaning systems with design informed by PPS mechanical contractors, data from literature, data from air cleaning sorbent manufacturers

While the HVAC system can improve the quality of indoor air, opportunities for improving outdoor air quality at the site require interventions such as tree walls or sound barriers. Our review of the existing literature shows that, designed properly, incorporating vegetation and/or sound barriers near traffic exposed areas can reduce concentrations of air pollutants 15-60%. To evaluate the potential of these systems for use at HTMS, wind tunnel testing will be conducted at the Wind Energy and Turbulence Lab at Portland State University. For this, modeling of the site has been successfully generated via virtual means. Construction of scaled models of HTMS and neighboring area is underway. Experimental cases have been identified.

4.2 Key recommendations

Portland State University has generated four key recommendations based on the findings and supporting data presented here. The recommendations are documented below along with a brief rationale that summarizes the body of evidence presented in detail in this report.

Recommendation #1: Student outdoor activities be limited at HTMS, especially during high traffic periods.

Rationale: Outdoor air quality at the site is impacted by I-5 traffic. 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.

Recommendation #2: The HVAC system be designed to include at least MERV16 filtration and dedicated sorbent beds capable of maintaining recommended media-air contact times for gas-phase pollutant removal.

Rationale: Filtration and sorption (chemi- and/or physi-sorption) are two proven technologies for treatment of particle and gas phase air pollutants. These systems require maintenance that is reasonably consistent with ongoing practices in PPS schools.

Recommendation #3: The HVAC system be designed such that outdoor ventilation air intakes are sited as far from I-5 as possible.



Rationale: Monitoring at HTMS indicates the site is impacted by emissions from the freeway and that levels of air pollutant are reduced with increasing distance from the freeway. Siting ventilation intake far from the freeway will reduce the levels of air pollutants introduced to the HVAC system, improving indoor air quality, reducing system maintenance needs, and improving resilience.

Recommendation #4: The building be commissioned with respect to HVAC balancing and building infiltration to ensure outdoor air enters the building via the dedicated outdoor air intake.

Rationale: Outdoor air can enter a building via ventilation or infiltration, the latter where outdoor air enters the building due to pressure difference across the building enclosure through cracks, gaps, or openings. It is recommended that the building shell facing I-5 be weatherized (made airtight) and rooms facing I-5 be operated at slightly positive pressure.

Recommendation #5: The efficacy of the air cleaning system be monitored periodically for breakthrough of gas-phase compounds and confirmation of removal efficiency of particulate matter.

Rationale: Gas-phase air treatment is subject to considerable uncertainty, as the removal efficiencies provided by the manufacturer may not be representative of replicate the actual environmental conditions. We suggest quarterly monitoring of VOCs via TD-GC-MS to verify expected removal efficiency and to evaluate for sorbent breakthrough. Particulate matter sensors should be installed permanently in several areas of the school in order to assess HVAC particulate performance on an on-going basis.

4.3 Limitations

This study was conducted to assess air pollutants to inform indoor and outdoor mitigation measures for Tubman Middle School. The suite of pollutants monitored were based on measurements needed for mitigation recommendations, assessment of prior ODEQ and EPA studies (see PSU proposal), recommendations from the Tubman Environmental Technical Advisory Committee, cost and PSU investigators' best professional judgment. There may be unmeasured air pollutants impacting the site that we did not measure (sulfur dioxide, for example). However, the recommended HVAC mitigation measures will significantly reduce the concentration of many atmospheric pollutants that we are aware of.

Due to the accelerated construction schedule for Tubman, the air monitoring timeframe was limited to 4-6 weeks. This monitoring window is short for completely evaluating the range of concentrations that could impact the site. However, based on our experience, the highest levels should be no more than a factor of 2



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or 3 of the current measurements, over the course of the year, with winter time levels being the highest. In this case, the anticipated design removal efficiency of the recommended HVAC control systems is expected to be capable of maintaining low indoor pollutant levels compared to urban background concentrations.



5 References

- Abhijith, K. V., and Sharad Gokhale. 2015. "Passive Control Potentials of Trees and On-Street Parked Cars in Reduction of Air Pollution Exposure in Urban Street Canyons." *Environmental Pollution* 204 (September): 99–108. <https://doi.org/10.1016/j.envpol.2015.04.013>.
- Abhijith, K. V., Prashant Kumar, John Gallagher, Aonghus McNabola, Richard Baldauf, Francesco Pilla, Brian Broderick, Silvana Di Sabatino, and Beatrice Pulvirenti. 2017. "Air Pollution Abatement Performances of Green Infrastructure in Open Road and Built-up Street Canyon Environments – A Review." *Atmospheric Environment* 162 (August): 71–86. <https://doi.org/10.1016/j.atmosenv.2017.05.014>.
- Akbari, H. 2002. "Shade Trees Reduce Building Energy Use and CO₂ Emissions from Power Plants." *Environmental Pollution* 116 (March): S119–26. [https://doi.org/10.1016/S0269-7491\(01\)00264-0](https://doi.org/10.1016/S0269-7491(01)00264-0).
- ASHRAE. 2015. "ASHRAE Position Document on Filtration and Air Cleaning." ASHRAE Position Document. <https://www.ashrae.org/File%20Library/docLib/About%20Us/PositionDocuments/ASHRAE-Position-Document-on-Filtration-and-Air-Cleaning.pdf>.
- Azimi, Parham, Dan Zhao, and Brent Stephens. 2014. "Estimates of HVAC Filtration Efficiency for Fine and Ultrafine Particles of Outdoor Origin." *Atmospheric Environment* 98 (December): 337–46. <https://doi.org/10.1016/j.atmosenv.2014.09.007>.
- Baldauf, Richard. 2017. "Roadside Vegetation Design Characteristics That Can Improve Local, near-Road Air Quality." *Transportation Research Part D: Transport and Environment* 52 (May): 354–61. <https://doi.org/10.1016/j.trd.2017.03.013>.
- Brugge, Doug, John L Durant, and Christine Rioux. 2007. "Near-Highway Pollutants in Motor Vehicle Exhaust: A Review of Epidemiologic Evidence of Cardiac and Pulmonary Health Risks." *Environmental Health* 6 (August): 23. <https://doi.org/10.1186/1476-069X-6-23>.
- Coder, Dr Kim D, and Warnell School. 2016. "Identified Benefits of Community Trees & Forests," 6.
- Fisk W. J., Faulkner D., Palonen J., and Seppanen O. 2002. "Performance and Costs of Particle Air Filtration Technologies." *Indoor Air* 12 (4): 223–34. <https://doi.org/10.1034/j.1600-0668.2002.01136.x>.
- Gallagher, John, Richard Baldauf, Christina H. Fuller, Prashant Kumar, Laurence W. Gill, and Aonghus McNabola. 2015. "Passive Methods for Improving Air Quality in the Built Environment: A Review of Porous and Solid Barriers." *Atmospheric Environment* 120 (November): 61–70. <https://doi.org/10.1016/j.atmosenv.2015.08.075>.
- Gallego, E., F. J. Roca, J. F. Perales, and X. Guardino. 2013. "Experimental Evaluation of VOC Removal Efficiency of a Coconut Shell Activated Carbon Filter for Indoor Air Quality Enhancement." *Building and Environment* 67 (September): 14–25. <https://doi.org/10.1016/j.buildenv.2013.05.003>.
- HEI. 2013. "Understanding the Health Effects of Ambient Ultrafine Particles." Health Effects Institute. January 23, 2013. <https://www.healtheffects.org/publication/understanding-health-effects-ambient-ultrafine-particles>.
- Hinds, William C. 1999. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*. 2 edition. New York: Wiley-Interscience.
- Kamboures, Michael A., Shishan Hu, Yong Yu, Julia Sandoval, Paul Rieger, Shiou-Mei Huang, Sherry Zhang, et al. 2013. "Black Carbon Emissions in Gasoline Vehicle Exhaust: A Measurement and Instrument Comparison." *Journal of the Air & Waste Management Association* 63 (8): 886–901. <https://doi.org/10.1080/10962247.2013.787130>.
- Kolobov, N. S., D. A. Svintsitskiy, E. A. Kozlova, D. S. Selishchev, and D. V. Kozlov. 2017. "UV-LED Photocatalytic Oxidation of Carbon Monoxide over TiO₂ Supported with Noble Metal



- Nanoparticles.” *Chemical Engineering Journal* 314 (April): 600–611.
<https://doi.org/10.1016/j.cej.2016.12.018>.
- Li, Ning, Constantinos Sioutas, Arthur Cho, Debra Schmitz, Chandan Misra, Joan Sempf, Meiyang Wang, Terry Oberley, John Froines, and Andre Nel. 2003. “Ultrafine Particulate Pollutants Induce Oxidative Stress and Mitochondrial Damage.” *Environmental Health Perspectives* 111 (4): 455–60.
- Li, Rui, Ya Meng, Hongbo Fu, Liwu Zhang, Xingnan Ye, and Jianmin Chen. 2017. “Characteristics of the Pollutant Emissions in a Tunnel of Shanghai on a Weekday.” *Journal of Environmental Sciences*, November. <https://doi.org/10.1016/j.jes.2017.11.015>.
- Mauderly, Joe L., and Jonathan M. Samet. 2009. “Is There Evidence for Synergy among Air Pollutants in Causing Health Effects?” *Environmental Health Perspectives* 117 (1): 1–6.
<https://doi.org/10.1289/ehp.11654>.
- McCarthy, M. C., J. F. Ludwig, S. G. Brown, D. L. Vaughn, and P. T. Roberts. 2013. “Filtration Effectiveness of HVAC Systems at Near-Roadway Schools.” *Indoor Air* 23 (3): 196–207.
<https://doi.org/10.1111/ina.12015>.
- Polidori, A., P. M. Fine, V. White, and P. S. Kwon. 2013. “Pilot Study of High-Performance Air Filtration for Classroom Applications.” *Indoor Air* 23 (3): 185–95.
<https://doi.org/10.1111/ina.12013>.
- “PORTAL | Portland State University | Portland Oregon.” n.d. Accessed April 16, 2018.
<https://portal.its.pdx.edu/>.
- Pugh, Thomas A. M., A. Robert MacKenzie, J. Duncan Whyatt, and C. Nicholas Hewitt. 2012. “Effectiveness of Green Infrastructure for Improvement of Air Quality in Urban Street Canyons.” *Environmental Science & Technology* 46 (14): 7692–99. <https://doi.org/10.1021/es300826w>.
- Raysoni, Amit U., Thomas H. Stock, Jeremy A. Sarnat, Mayra C. Chavez, Stefanie Ebel Sarnat, Teresa Montoya, Fernando Holguin, and Wen-Whai Li. 2017. “Evaluation of VOC Concentrations in Indoor and Outdoor Microenvironments at Near-Road Schools.” *Environmental Pollution* 231 (December): 681–93. <https://doi.org/10.1016/j.envpol.2017.08.065>.
- Selby, Gary W., and Robert M. Counce. 1988. “Aqueous Scrubbing of Dilute Nitrogen Oxide Gas Mixtures.” *Industrial & Engineering Chemistry Research* 27 (10): 1917–22.
<https://doi.org/10.1021/ie00082a026>.
- Sidheswaran, Meera A., Hugo Destailats, Douglas P. Sullivan, Sebastian Cohn, and William J. Fisk. 2012. “Energy Efficient Indoor VOC Air Cleaning with Activated Carbon Fiber (ACF) Filters.” *Building and Environment*, International Workshop on Ventilation, Comfort, and Health in Transport Vehicles, 47 (Supplement C): 357–67. <https://doi.org/10.1016/j.buildenv.2011.07.002>.
- Tobías, Aurelio, Ioar Rivas, Cristina Reche, Andrés Alastuey, Sergio Rodríguez, Rocío Fernández-Camacho, Ana M. Sánchez de la Campa, Jesús de la Rosa, Jordi Sunyer, and Xavier Querol. 2018. “Short-Term Effects of Ultrafine Particles on Daily Mortality by Primary Vehicle Exhaust versus Secondary Origin in Three Spanish Cities.” *Environment International* 111 (February): 144–51. <https://doi.org/10.1016/j.envint.2017.11.015>.
- US EPA, OAR. 2014. “Ozone Generators That Are Sold as Air Cleaners.” Overviews and Factsheets. US EPA. August 28, 2014. <https://www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners>.
- US EPA, ORD. 2016. “Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality.” Overviews and Factsheets. US EPA. 2016. <https://www.epa.gov/air-research/recommendations-constructing-roadside-vegetation-barriers-improve-near-road-air-quality>.
- Valavanidis, A., K. Fiotakis, and T. Vlachogianni. 2008. “Airborne Particulate Matter and Human Health: Toxicological Assessment and Importance of Size and Composition of Particles for Oxidative Damage and Carcinogenic Mechanisms.” *Journal of Environmental Science and Health, Part C* 26 (4): 339–62. <https://doi.org/10.1080/10590500802494538>.



- Vos, Peter E. J., Bino Maiheu, Jean Vankerkom, and Stijn Janssen. 2013. "Improving Local Air Quality in Cities: To Tree or Not to Tree?" *Environmental Pollution (Barking, Essex: 1987)* 183 (December): 113–22. <https://doi.org/10.1016/j.envpol.2012.10.021>.
- Wania, Annett, Michael Bruse, Nadège Blond, and Christiane Weber. 2012. "Analysing the Influence of Different Street Vegetation on Traffic-Induced Particle Dispersion Using Microscale Simulations." *Journal of Environmental Management* 94 (1): 91–101. <https://doi.org/10.1016/j.jenvman.2011.06.036>.
- Yang, Jun, Joe McBride, Jinxing Zhou, and Zhenyuan Sun. 2005. "The Urban Forest in Beijing and Its Role in Air Pollution Reduction." *Urban Forestry & Urban Greening* 3 (2): 65–78. <https://doi.org/10.1016/j.ufug.2004.09.001>.
- Yang, Jun, Qian Yu, and Peng Gong. 2008. "Quantifying Air Pollution Removal by Green Roofs in Chicago." *Atmospheric Environment* 42 (31): 7266–73. <https://doi.org/10.1016/j.atmosenv.2008.07.003>.
- Zheng, Xuan, Ye Wu, Jingkun Jiang, Shaojun Zhang, Huan Liu, Shaojie Song, Zhenhua Li, Xiaoxiao Fan, Lixin Fu, and Jiming Hao. 2015. "Characteristics of On-Road Diesel Vehicles: Black Carbon Emissions in Chinese Cities Based on Portable Emissions Measurement." *Environmental Science & Technology* 49 (22): 13492–500. <https://doi.org/10.1021/acs.est.5b04129>.
- Zhu, Yifang, William C. Hinds, Seongheon Kim, and Constantinos Sioutas. 2002. "Concentration and Size Distribution of Ultrafine Particles near a Major Highway." *Journal of the Air & Waste Management Association (1995)* 52 (9): 1032–42.



6 Appendices

6.1 Additional analysis

6.1.1 Harriet Tubman Metals Sampling – daily averages

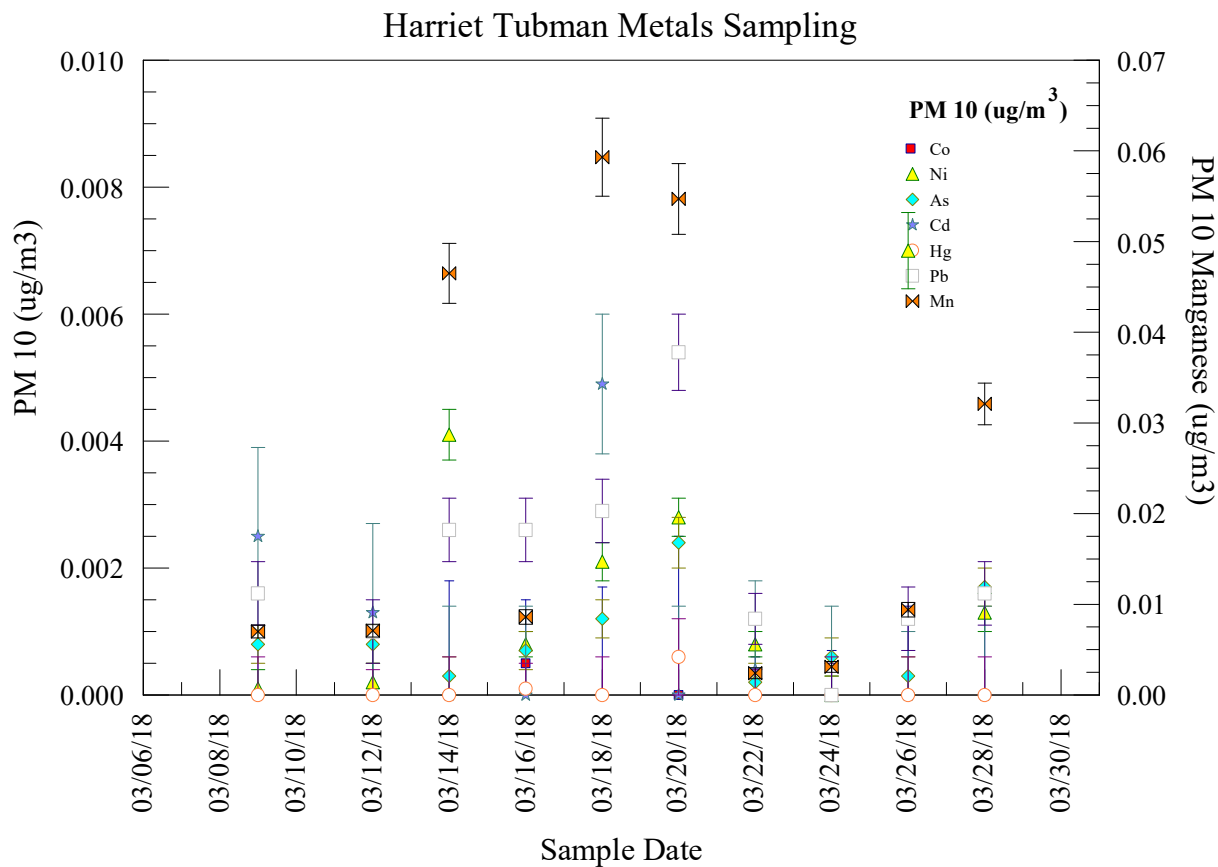


Figure A1. Day to day variation in metals sampled at the Harriet Tubman Middle School site.

6.1.2 Gravimetric particulate matter measurements

Gravimetric particulate matter samples (PM_{2.5}) are shown below in Figure XX. These samples were taken from the ARA samplers placed on the HTMS roof for the period spanning 3/13 – 3/27/2018.

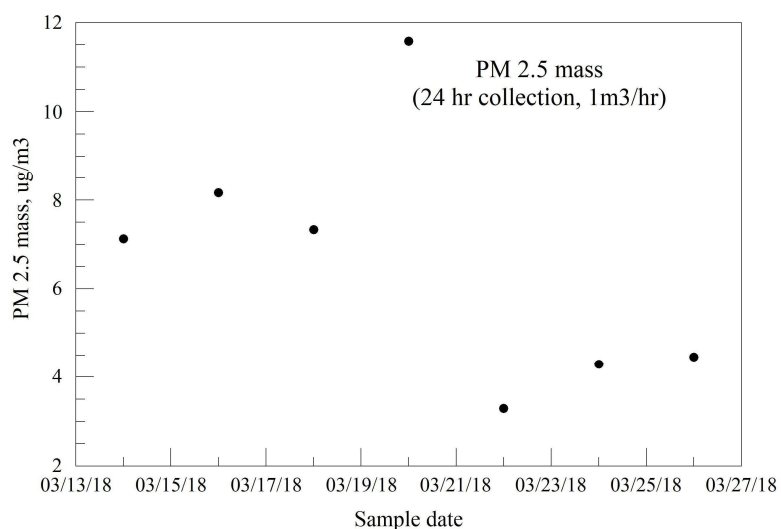


Figure A2. Summary of gravimetric PM monitoring at HTMS.

6.1.3 Black carbon regression, Flint vs. I-5

Figure A3 shows a regression of all data collected between the I-5 and Flint Ave. deployment locations. A simple linear regression across the deployment period (April 6th – April 10th) shows that, across the entire period, the I-5 levels paired with the corresponding Flint BC levels are ~28% higher in magnitude.

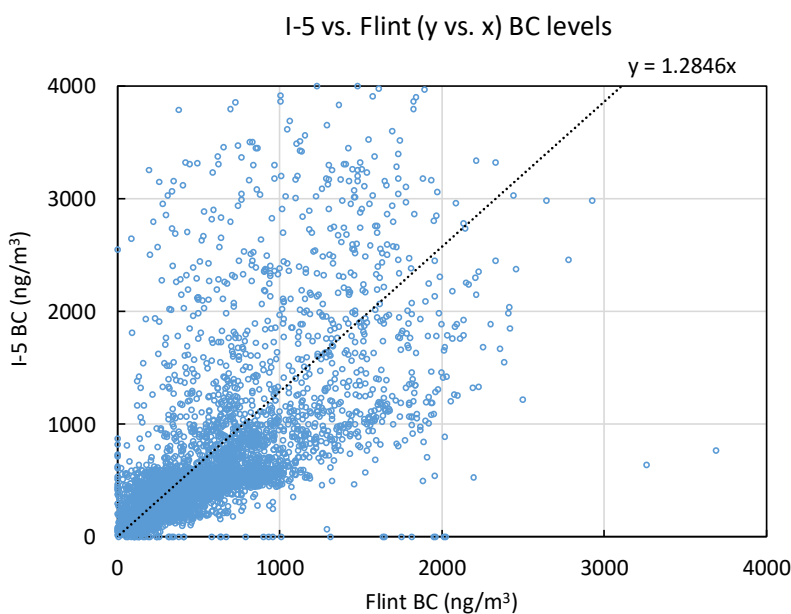


Figure A3. Comparison of BC data during co-deployment of BC monitors to Flint Ave and I-5.



6.1.4 Traffic data (summarized for March 13-29)

Portland State University houses PORTAL, a centralized database that facilitates collection and sharing of regional transportation data (PORTAL | Portland State University | Portland Oregon). Using this database, we accessed historical traffic records for a representative period that coincided with full deployment of the intensive air quality monitoring campaign shown previously in Section 2.3. While an in-depth analysis of traffic patterns is out of scope of this study, the results of a diurnal analysis of traffic shown in Figure A4 of traffic patterns on weekdays (Monday-Friday) is informative in the context of air quality impacts to Harriet Tubman Middle School. The data shown in Figure A4 represent the sum of two stations representing northbound and southbound traffic in proximity to HTMS (Northbound station 2DS010 and Southbound station 2R018). In general, traffic volumes are roughly consistent with annual averages reported by the Oregon Dept. of Transportation for this portion of I-5, averaging ~150,000 vehicles per day.

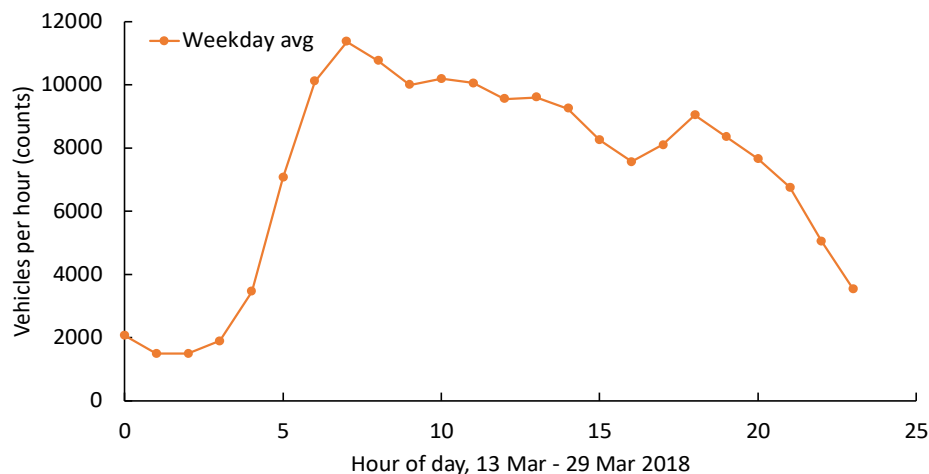


Figure A4. Summary of hourly averaged vehicle counts on I-5 near Harriet Tubman Middle School for weekdays between 13-29 March (Monday-Friday only).

During weekdays, the morning traffic began ~ 4 AM and peaked at approximately 06:00-07:00 AM, generally consistent with trends observed in air quality data. Given that vehicle emissions are a major source of air pollution at HTMS, traffic trends at the HTMS site provide important context for analyzing and understanding time-series measurements of air pollution. As Portland, OR continues to grow and evolve in its transportation infrastructure, it is recommended the traffic trends at these stations be periodically reviewed and compared with building and school operational and educational schedules. For example, building ventilation systems could be programmed to anticipate daily trends in traffic and respond with pressurization/ventilation accordingly.



6.2 Quality assurance and quality control

This project required very rapid deployment of monitoring equipment (over 10 instruments). Our monitoring goal is to assess the level and types of air pollutants impacting the site in order to inform indoor and outdoor mitigation options. 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 A1. Summary of quality assurance and quality control measures.

Parameters Monitored	Instrument Manufacturer/Make	QA/QC employed
Nitrogen oxide, nitrogen dioxide	Teledyne T200P Teledyne T200	Ecotech 1100 Calibrator, EPA Protocol Gas Calibration before deployment Return to lab monthly for recal.
Carbon monoxide	Ecotech Serinus 30	Factory calibration Return to lab monthly for recal.
Black Carbon	Magee Scientific 55	Factory calibration Return to lab monthly for recal.
PM 2.5. (mass/metals) PM 10 (metals)	ARA Instrument	Flow calibration before deployment Return to lab monthly for recal. Metals/mass analysis by Chester
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



6.3 HVAC air cleaning recommendations

6.3.1 PCO vs. Sorption VOC removal systems with mechanical contractor (email conversation paraphrased and edited for clarity)

There are at least two technologies we could consider: PCO (photocatalytic oxidation systems) systems or sorbent systems. My initial thoughts on this, based on what I've seen in the literature on PCO and knowledge of their principle of operation, is that we should be skeptical. In independent testing of the PCO systems I've seen evidence that the degradation of organics may not be complete (i.e., may generate harmful byproducts from the VOCs instead of converted to CO₂ and water vapor) and that the systems generate ozone as a byproduct, which is in and of itself a harmful compound. They are also more costly to operate and maintain, and will be more complicated to operate for your facilities staff.

That leaves sorbent systems. The ideal situation is we measure what VOCs are present at the site, then work with a company who can tailor sorbents and media bed depth to our specific gas-phase pollutant mixture and levels of concern. Two such companies are listed at the end of this email who may be able to assist with this (not in any order of preference). There are several companies that also claim to have proprietary sorbents/systems for gas-phase air pollutant treatment. Two companies are listed below that manufacture such systems (again, not in any order of preference). Getting an idea of practical design considerations for the proprietary systems would require discussion with the manufacturer - these are advertised as more standalone, turnkey type systems, which may have some advantages.

Based on the literature I've seen for VOC removal by sorbents in HVAC systems, the approach nearly always includes activated carbon as one sorbent, so I think Andy's thought there is correct. Given that we are expecting potentially elevated NO_x levels as well as possibly elevated polar VOCs (e.g., formaldehyde, which is not effectively removed by activated carbon) I would also recommend a potassium permanganate impregnated sorbent. I spoke today with the Portland Camfil rep to get their initial thoughts. Based on their rep's input, he thought a 12" media bed (specific to Dan's option 1) would be conservative. Camfil offers three ways of integrating a variety of sorbent media into the system - either impregnated on typical HVAC filters, as standalone filter-type housings that contain a sorbent media, or as a container in-line in the ducting that contains a packed bed of media. I've worked with the packed-bed type in the past and it can be very cumbersome to remove media and reload. My thought would be to design for a series of the filter-type sorbent housings that contain a variety of tailored sorbent media that can be installed downstream the PM filter. My thought would be that this would allow us to design



conservatively and independent from the filtration for PM. Camfil (or a competitor to Camfil) could advise on details more relevant to the design re: required media contact time and resulting pressure drop. I spoke with Mario in the Portland office, and can pass along his contact information if you/Mortensen want to pursue that option.

So, if the design must commence now, my thought would be to have Mortenson/Alliant touch base with a few manufacturers about what would constitute a conservative design for VOC removal in terms of mass of media needed (perhaps Camfil and Intramicon). If the standalone systems are of interest, Johnson/York or Enverid may be able to advise on design particulars. I can make myself available to be a part of those discussions, if it is helpful. I think the issue we want to avoid is specifying too small of a filter/media bed that is either ineffective and/or requires very frequent changeout. Without knowing particulars about adsorption isotherms (which the manufacturer should know) or breakthrough data, as well as the concentration of the compounds we are dealing with it's difficult to know what exactly the dimensions of a housing should be. Again, I think a company like Camfil can help work through a conservative design (e.g., provisioning for three or more filter-type media housings (in series) that could be left empty if not needed).

6.3.2 Recommendations made to HVAC contractor

The following summarizes questions from an HVAC contractor (red) and answers provided by PSU (black)

Is the MERV 16 final filter redundant when using the carbon air filter upstream? And if so, can it be deleted? (given the massive surface area and particle retention of activated carbon)

The MERV 16 filter is not redundant. I think it is essential that the activated carbon bed be protected from incoming particulate matter. If PM were to deposit on the activated carbon, it would clog pores in the media that would prevent the VOCs and other gas-phase compounds we are targeting with this media from interacting with the adsorption sites on the media. This would effectively shorten its useful life. For this reason, I'd recommend placing the carbon filters downstream of the MERV 8 pre-filter and HEPA filter. This may make the MERV 8 pre-filter redundant, but my understanding is that that arrangement dramatically increases the lifespan of the more expensive HEPA filter. I would expect a similar concept to hold true for the gas-phase media - additional PM filtration afforded by the HEPA filter will maximize the useful lifespan of the media to be closer to that of the specifications provided by the manufacturer.



Is a shorter Carbon filter tube, say 18" or 10 inch, acceptable? It is understood that the residence time decreases, but so does the wt of a 24x24 module. (96 lbs vs. 72 lbs vs. 38 lbs per 24x24 module per canister length 23/18/10 in. respectively)

The impact of reducing the length of the filter will cause the target compounds to "breakthrough" the media bed more rapidly due to decreased mass of adsorbent. It'd be my recommendation to maintain as close to the 0.1 second contact time that Camfil recommends for their stated removal efficiencies and capacities. This would mean maintaining the recommended masses of media. I would need to request additional information from Camfil to make a quantitative estimate of the the impact of reducing mass on breakthrough, but to a rough approximation the breakthrough time scales linearly with the mass of carbon present. I will ask Mario from Camfil (unless you are working with a different rep?) for the additional parameters we would need to make a rough estimate of this impact on breakthrough. I would think it would mean a trade-off in operation, in that the media would need to be changed out more frequently.

Is there a different or preferred carbon media from Camfill farr options on the data sheet that is a best fit for Tubman?

My recollection from the discussions with Camfill-Farr is that we could design a custom blend of sorbent media based on our monitoring data. My discussions with Mario indicated that Camfil was recommending the LGX048 media. He had previously sent some initial removal efficiency data on this sorbent. Perhaps you can fill me in if there was a reasoning for selecting the CEX004. Camfil's literature indicates they are both reasonable broad spectrum activated carbon, but my thought is that we should likely target a % of the media to include an activated alumina impregnated with potassium permanganate (Campure 4,8 or 9) to target NO/NO₂. The final blend would depend on the air quality data analysis at this site. The system pressure drop reporting in the literature I have from camfil reads as non-specific within the CamCarb CF family, so my initial presumption is that perhaps the final selection of the media blend could wait until the outdoor AQ monitoring is complete without impeding the HVAC mechanical design?