Harriet Tubman Middle School

Indoor and Outdoor Air Quality Health Risk Assessment

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1.0 Executive Summary

The design and installation of the HVAC system for Harriet Tubman Middle School was developed out of concern for the health of students and staff. Portland Public Schools recognized that the outdoor air at the school was impacted by traffic-related air pollution from I-5, and potentially by area industry. Preliminary air monitoring conducted in March and April of 2018 confirmed the need for an HVAC system with filtration for particles and gases to prevent sustained daily exposure. Renovation of the school building and installation of the HVAC system was completed in August. To evaluate the performance of the particle filters and the charcoal sorption bed, a new round of monitoring was conducted in September and October, with measurements made at the air intake and within the air handling units of the HVAC system. These measurements confirmed that the HVAC system achieved protective levels of indoor air quality at the time of occupancy. A third round of monitoring was conducted at the end of the school year, in April and May of 2019. Measurements at this time confirmed the HVAC system continued to provide a high level of removal of particles and gases.

This report provides an analysis of the adequacy of the HVAC system to minimize the health risks posed by air pollution at Harriet Tubman Middle School. The measurements of the various components of traffic-related air pollution are evaluated against available federal and state air quality standards, and published governmental and scientific literature. The report also evaluates the potential health risks from exposure to outdoor air pollution during physical education and lunch periods.

The five key conclusions from the health analysis are:

1. Indoor levels of air pollution are very low. For each of the pollutants monitored, the filtered air delivered to the classrooms and interior spaces of the school is clean, safe and supportive of health for students and staff.
2. Particle and gas removal by the HVAC system and its filtration systems remained consistently high across the school year.
3. Outdoor levels of particulate matter (PM_{10}, and $PM_{2.5}$) and the gases carbon monoxide (CO) and nitrogen dioxide (NO_2) are below federal air quality standards, and therefore pose no concern for health during physical activities.
4. Certain pollutants associated with diesel exhaust (ultrafine particles and black carbon) were observed at elevated levels typical of locations near heavily travelled highways. The HVAC system provides a high level of protection against exposure in the classrooms and interior of the building.
5. The health risks of short-term exposures to diesel pollution are not known, and regulatory limits have not been established. However, sufficient toxicological and epidemiological evidence exists to recommend that outdoor physical education activities be scheduled in the later morning and afternoon when traffic pollution is much lower. This recommendation is made with an abundance of caution, recognizing that some students, such as those with asthma, may be more susceptible to adverse effects of traffic-related air pollution.

2.0 Introduction

Increasing public health attention to traffic-related air pollution (TRAP) compelled Portland Public Schools (PPS) to design and install a heating, ventilation, and air conditioning (HVAC) system with filtration for particles and gases during the modernization of Harriet Tubman Middle School. The predominant concern was the reduction of day-to-day exposures to TRAP that have been associated with reduced lung growth in children, and increased risk for the development (onset) of asthma and exacerbation (triggering) of asthma attacks. The commitment to install the HVAC system by PPS also acknowledged emerging health research concerns for individual components of TRAP, specifically diesel particulate matter. Extensive air monitoring studies were conducted by scientists from Portland State University to characterize the outdoor air quality and confirm the adequacy of the performance of the HVAC filtration system to provide clean air to classrooms and indoor spaces at the school. Air quality measurements were first made in the April 2018, and were conducted again in the September and October following installation of the HVAC system and building occupancy. Another cycle of measurements was made in April and May of 2019 to evaluate outdoor-indoor conditions after 7 months of air handling system operation.

The PSU team conducted a monitoring on a comprehensive set of individual pollutants that comprise TRAP. The set of pollutants include the "criteria pollutants" carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter (PM_{10} and $PM_{2.5}$) whose health effects are widely recognized and for which federal regulatory standards exist (NAAQS Table). Ultrafine particles UFP), black carbon (BC), and volatile organic compounds (VOCs) are constituents of diesel exhaust and these forms of PM were also monitored. Specific air quality standards do not exist for these diesel pollutants, however, evidence from animal toxicology research and ongoing epidemiologic studies support concern for children as particularly susceptible to the adverse respiratory effects of long-term exposure to diesel particulate pollution (HEI 2010; HEI 2013; Guarnieri and Balmes 2014).

This report provides an opinion on the health risks posed to students and staff at Harriet Tubman Middle School using the measured exposures in outdoor and indoor air. This analysis follows a weight-of-evidence approach that applies federal health-based standards when available, and applies information from published studies for pollutants which lack regulatory guidelines.

3.0 Carbon Monoxide

3.1 Relevant Background

Carbon monoxide (CO) is a toxic asphyxiant gas that is hazardous because of its specific ability to bind to hemoglobin and to reduce the ability of the blood to deliver oxygen to tissues. As a component of motor vehicle emissions, CO penetrates to indoor spaces with high efficiency because this gas has very low chemical reactivity. These same physical and chemical properties limit engineering abilities to economically remove CO gas when present in the intake air of building ventilation systems. To protect public health, regulatory emphasis has been placed on reducing CO emissions from motor vehicles thorough the cleaner formulations of gasoline fuels, motor/vehicle inspection maintenance programs, and reducing emissions from wood stoves, fireplaces, open burning, and industrial sources. CO trends

for Oregon and Portland have steadily declined over the past 5 decades and currently the second highest 8-hour average occurring in a year is less than 2 ppm (https://www.oregon.gov/deq/FilterDocs/2017aqannualreport.pdf). Although CO from motor vehicle emissions disperses quickly under most conditions, poor traffic flow and congestion can lead to elevated exposures for motor vehicle occupants and persons in close proximity to highways. CO concentrations measured at microscale sites have declined in the same proportions as concentrations recorded at monitors representing larger urban regions. Ambient monitoring at near-road locations indicate that the federal standards are not exceeded, and this protection is attributed to greatly improved control of motor vehicle emissions (e.g., clean burning fuels, improved light-duty engine design, and catalytic convertors). Measurements of ambient CO at the Oregon DEQ I-5 Tualatin near-roadway air monitoring station have not recorded exceedances of federal standards during 2015 to 2017 (maximum 8-hour averages = 1.4 ppm).

The health risks of CO have been long recognized and CO is one of the original six "criteria" air pollutants defined in the Clean Air Act of 1970. The current National Ambient Air Quality Standard (NAAQS) for carbon monoxide is 35 ppm over a 1-hour averaging time and 9 ppm over an 8-hour averaging time (https://www.epa.gov/criteria-air-pollutants/naaqs-table). These levels are based on an extensive evidence base from epidemiologic studies and controlled exposure studies on human subjects (https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=218686&CFID=78776911&CFTOKEN=81884369). The two averaging times prevent blood carboxyhemoglobin levels from reaching 2%, the level at which chest pain (angina pectoris) is triggered in exercising adults with coronary artery disease, and to protect pregnant women and the developing fetus from hypoxic stress and low birth weight outcomes. As a point of reference, carboxyhemoglobin concentrations in cigarette smokers range from 3-8% and symptoms of intoxication and acute poisoning generally appear above 20%, although symptoms and clinical states of acute CO poisoning correlate poorly with level of carboxyhemoglobin (Raub 2000).

3.1.2 HTMS Outdoor and Indoor Levels

The distribution of school-day average CO concentrations during Portland State University's Phase II (September-October) and Phase III (April-June) monitoring periods is presented in Figure 1. During the Fall, outdoor carbon monoxide levels averaged 0.4 ppm (432 ppb) over the 9 AM to 4 PM school day. The maximum school-day average was 1.4 ppm (1434 ppb). 95 percent of the outdoor air school-day averages in the Fall were below 0.6 ppm (639 ppb).

In the Fall, measurements of CO levels at the supply air point of the HVAC system, representing air that has been filtered of particles and passed through the charcoal bed, contained substantially lower concentrations of CO relative to the outdoor air. Approximately 44% removal was observed. However, measurements of the return air were essentially equal to the concentrations measured in outdoor air, suggesting CO infiltration through the building envelope.

In the Spring, the outdoor average level was 0.09 ppm (90.8 ppb), considerably lower than the Fall average. 95% of the school-day averages were below 0.2 ppb (236 ppb). Concentrations in the supply air were identical with the outdoor air. Although CO has not been removed from the air supplied to the

interior space of the school, these levels are below the NAAQS of 9 ppm averaged over 8 hours. Measurements of CO in the return air, representing the mixed air of the entire interior of the school, averaged 0.07 (73.9 ppb). This small difference in the air concentration is not appreciable, and is supportive of improved balancing of air delivery and minimization of infiltration in the Spring.

3.1.3 Implications for Health

Although the levels of CO in outdoor air were higher in the Fall than in the Spring, these school-day average levels of 0.4 ppm and 0.2 ppm are well below the NAAQS 9 ppm 8-hour average. Even the highest school-day average of 2.2 ppm is only one-fourth the level of the NAAQS. Thus, exposures of students and staff to CO at Harriet Tubman Middle School do not differ from those expected to be received at their residences or during commuting.

Measurements of ambient CO in the Portland area by the Oregon DEQ at Portland monitoring stations and do not exceed the NAAQS. For example, during 2008-2017, maximum 8-hour averages measured by the DEQ at the SE Lafayette neighborhood site ranged from 1.3 to 3.1 ppm, and for the near-roadway site at Tualatin I-5 during 2015-17 maximum 8-hour averages range from 1.3 to 1.4 ppm (Oregon Air Quality Annual Report 2017).

In summary, the monitoring data from Fall 2018 and Spring 2019 at HTMS confirm that concentrations of CO are consistently low and do not present a health risk to students and staff.

3.2 Nitrogen Dioxide

3.2.1 Relevant Background

Nitrogen dioxide (NO_2) is an irritant gas that combines with water on respiratory tract tissues to form nitric (HNO_3) and nitrous (HNO_2) acids. When inhaled in high concentrations, NO_2 results in edema and bronchopneumonia. At lower concentrations, short term (acute) exposures to NO_2 are associated with exacerbation of asthma caused by the constriction of the smooth muscle of the conducting airways and increased mucous production. Longer term exposures at low levels are associated with the development of asthma in children. The health effects of NO_2 are well documented in experimental studies in animals, and in controlled human exposure and epidemiologic studies (https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879). As a chemical class, nitrogen oxides are principal components of motor vehicle emissions, and NO_2 is specifically regulated as a criteria pollutant under the Clean Air Act. In recognition of the need to protect against both acute and chronic exposures, the current NAAQS for NO_2 are 100 ppb averaged over 1 hour and 53 ppb averaged over 1 year (https://www.epa.gov/criteria-air-pollutants/naaqs-table).

Over the past decade, Oregon DEQ monitoring data at the Portland neighborhood site, highest hourly averages of NO_2 have been near 40 ppb (https://www.oregon.gov/deq/FilterDocs/2017aqannualreport.pdf). Over 2015 to 2017, the daily maximum concentrations from the I-5 near-roadway station in Tualatin has also tracked in the 35-40 ppb range. Thus, the maximum concentrations measured at urban locations in Portland are well below

the federal standard of 100 ppb. Similarly the annual NO_2 average for the neighborhood and near-roadway monitoring sites has consistently tracked near 10 ppb and 13 ppb, respectively; also well below the federal standard of 53 ppb.

3.2.2 HTMS Outdoor and Indoor Levels

The distribution of school-day average NO_2 concentrations during the Fall and Spring monitoring periods is presented in Figure 2. In the Fall, outdoor NO_2 levels averaged 13.0 ppb over the 9 AM to 4 PM school day. The highest school-day average was 67.6 ppb. 95 percent of the daily averages were below 30 ppb, and 75 percent were below 20 ppb. The mean supply air average was 0.89 ppb, indicating a high level of removal by the air handling system. The mean NO_2 levels in return air was 6.92 ppb. Despite the apparent infiltration of outdoor NO_2 through the building envelope, indoor NO_2 levels are approximately one-half of the levels observed in outdoor air.

In the Spring monitoring period, the school-day average of 7.3 ppb was substantially lower than concentrations observed in the Fall. Supply air concentration averaged 2.8 ppb, again indicating substantial removal by the HVAC system. Return air NO_2 concentrations averaged 0.9 ppb, substantially lower than the supply air and possibly indicating reaction of NO_2 with indoor surfaces and occupants.

Outdoor NO_2 levels measured by passive samplers placed on the school grounds, the adjacent city park, and neighborhood streets provided one-week average measurements that were comparable to the levels measured in outdoor air at the HVAC intake unit, and demonstrated reductions in levels with increasing distance from the I-5 highway.

3.2.3 Implications for Health

NO_2 is not simply an indicator of other traffic-related pollutants, and this oxidant gas has independent effects on the respiratory system. High short-term exposures are associated with asthma attacks, and with bronchoconstriction and airway inflammation. These health effects are observed independent of other traffic-related pollutants, such as $PM_{2.5}$ and black carbon. Further, repeated and persistent exposure to NO_2 across years results in the development of allergic responses and structural changes to the airways of the child, damaging lung growth. Because the respiratory effects of NO_2 appear to occur across both short- and long-term time scales, the U.S. EPA developed standards for both 1-hour and annual averaging times to provide protection against triggering asthma attacks, and against asthma development.

Indoor concentrations of NO_2 in the school, as represented by the levels measured in return air to the HVAC system in the Fall and Spring, averaged 6.9 and 0.88 ppb, respectively. These school levels are very low relative to the 1-hour standard of 100 ppb and the annual standard of 53 ppb, and are likely lower than levels of exposure experienced by students and staff in their homes and neighborhoods.

Outdoor concentrations averaged 13 ppb across the 9 AM to 4 PM school day in the Fall and 7 ppb in the Spring. These levels are higher than neighborhood background and reflect the influence of traffic

emissions from I-5, but they are well below the federal standards of 100 ppb 1-hour average and 53 ppb annual average.

The maximum school-day average concentration was 67.6 ppb in the Fall of 2018, and 75% of school-day averages during this monitoring period were less than 20 ppb. These levels are substantially lower than the concentrations known to trigger changes in lung function and symptoms in panel studies of asthmatic children (U.S. EPA *Integrated Science Assessment for Nitrogen Oxides*, 2016). The concentrations associated with increased airway responsiveness range from 200 to 300 ppb for 30 min, and 100 ppb for 1 hour. The concentrations associated with allergic inflammation are 581 ppb for 15 min and 260 ppb for 30 min. Therefore, the observed levels of NO_2 in outdoor air surrounding the school buildings and the park are below levels of concern for this susceptible group of children.

3.3 Particulate Matter

3.3.1 Relevant Background

As type of air pollution, particulate matter (PM) includes finely divided solid and liquid materials that are suspended and move in the air. The size distribution of particles can vary greatly, and the mixtures of depend on the types of sources. The smaller size classes of particles are of greater health concern because they have the capability to bypass the normal defenses of the upper respiratory tract and can be inhaled deeply into the lungs where they can be deposited and cause harm.

Two principal classes of particle sizes are used in federal air pollution standards: "PM_{10}" which are particles smaller than 10 microns in diameter and able to be inhaled through the nose. Soil dust, pollen, and mold particles are in this size range. "$PM_{2.5}$" is comprised of particles that are 2.5 microns and smaller, and includes the class of particles that are called "fine" (diameters of 0.1 to 2.5 μm) and "ultrafine" (0.01 to 0.1 μm). Combustion processes generate this size fraction, and some of the fine and ultrafine particles of $PM_{2.5}$ may contain liquid acid condensates, organic compounds, and heavy metals, increasing their toxic potential. The health effects of particulate matter include respiratory system irritation, lung damage, the development of chronic obstructive pulmonary disease (COPD), and heart attacks (U.S. EPA. *Integrated Science Assessment for Particulate Matter (External Review Draft)*, 2018).

Particulate matter air pollution is measured as weight (mass) per cubic meter of air, and the federal standards are defined using these units. The NAAQS for PM_{10} is 150 micrograms per cubic meter ($\mu g/m^3$) averaged over a 24-hour period. The NAAQS for $PM_{2.5}$ is 35 $\mu g/m^3$ averaged over a 24-hour period and 12 $\mu g/m^3$ averaged over one year.

3.3.2 HTMS Outdoor and Indoor Levels

The school-day average levels of outdoor PM_{10} were relatively low during the Fall monitoring period (Figure 3). At this time, PM_{10} averaged 2.58 $\mu g/m^3$ with an interquartile range of 1.40 to 3.30 $\mu g/m^3$. PM_{10} concentration in the supply air averaged 0.14 $\mu g/m^3$ indicating high removal capacity by the HVAC filtration system. A small increase of PM_{10} was observed in the return air, which averaged 1.20 $\mu g/m^3$, and can be attributed to re-suspended interior dust and infiltration. Outdoor PM_{10} levels were higher in

the Spring, with average levels at 7.39 μg/m^3 and an interquartile range of 5.28 to 9.33 μg/m^3. High removal efficiency was observed again; supply air concentrations of PM_{10} averaged 3.08 μg/m^3 and the return air average concentration were essentially the same at 3.11 μg/m^3. In summary, the outdoor levels of PM_{10} are considerably lower than the 150 μg/m^3 per 24-hour average NAAQS, and the school's HVAC system effectively filters PM_{10} to very low indoor levels.

Outdoor air concentrations of $PM_{2.5}$ were also consistently low in both the Fall and Spring (Figure 4). In the Fall, $PM_{2.5}$ averaged 2.13 μg/m^3 with an interquartile range of 1.06 to 2.86 μg/m^3. Thus, outdoor levels are below the NAAQS of 35 μg/m^3 24-hour average and 12 μg/m^3 annual average. In the Spring, $PM_{2.5}$ averaged 2.69 μg/m^3 with an interquartile range of 1.25 to 3.85 μg/m^3. Effective removal capacity of $PM_{2.5}$ by the HVAC system was observed in both seasons. Return air concentrations averaged 0.72 μg/m^{3}in the Fall and 0.71 in the Spring, demonstrating very low $PM_{2.5}$ exposures to building occupants.

3.3.3 Implications for Health

Both PM_{10} and $PM_{2.5}$ in outdoor air were measured at concentrations below the federal standards in both the Fall and Spring seasons, supporting the conclusion that particulate matter pollution from I-5 does not present a health hazard for students and staff. The HVAC system was specifically designed to remove particles in this inhalable and respirable size range, and large removal efficiencies were observed in both monitoring seasons, providing evidence of air handling system stability across the entire school year. Because students are in the filtered indoor environment during the majority of the school day, their total exposure to particulate matter is likely reduced relative to the exposures they would have received at their residences full-time.

The potential health risks associated with short-term particulate matter exposure during outdoor activities must be considered. The U.S. EPA's *Integrated Science Assessment for Particulate Matter (2018)* combines the evidence from controlled animal studies employing short-term exposures on markers of lung injury and oxidative stress. These toxicological studies provide insight into the potential mechanisms of respiratory health effects (biological plausibility) and assist with the interpretation of epidemiologic evidence. While multiple studies of long-term $PM_{2.5}$ exposure provide coherent evidence to support a causal role in the development of asthma in children, the evidence to support short-term effects on asthma attacks is much more limited. Collectively, the available epidemiologic studies on children with asthma in U.S. cities provide weak support for aggravation of asthma symptoms at 24-hour average concentrations typically experienced in urban areas. The shared limitations of these studies include reliance on self-reported symptoms, incomplete adjustment for co-occurring pollutants, use of modelled personal exposure from central monitoring sites, and the potential for the constituents of $PM_{2.5}$ (elemental carbon, ultrafine particles), rather than $PM_{2.5}$ mass itself, to explain the observed outcomes. Further, the ambient concentrations in these studies are substantially higher than levels observed outdoors at the school where average school-day $PM_{2.5}$ levels in the Fall of 2018 were 2.13 μg/m^3. Mean 24-hour $PM_{2.5}$ concentrations are greater than 15 μg/m^3 in studies of emergency department visits and hospital admissions for asthma (Sarnat et al. 2015; Ostro et al. 2016), and those studies considering respiratory symptoms and asthma medication (Rabinovitch et al. 2006; Mann et al. 2010; Spira-Cohen et al. 2011).

In summary, the outdoor concentrations of PM_{10} and $PM_{2.5}$ at HTMS are below federal standards, and are safe for students and staff, including those with asthma. The school's HVAC system further reduces these concentrations to create an indoor environment which has very low levels of PM_{10} and $PM_{2.5}$ pollution.

3.4 Black Carbon

3.4.1 Relevant Background

Black carbon (BC) is an important component of particulate matter, and is emitted during the combustion of biomass and fossil fuels. In particular, BC in the ultrafine particle fraction is used as a marker of diesel exhaust and is argued to be a useful alternative measure to particle mass (PM_{10} and $PM_{2.5}$) because health risks may be qualitatively and quantitatively different due to unique physical and chemical properties of BC (Jannsen et al. 2011). Diesel exhaust is a complex mixture of gases and ultrafine particles of a diameter less than 0.1 μm. No single chemical constituent of diesel exhaust can serve as a unique marker of exposure (Grahame, Klemm, and Schlesinger 2014), but taken together, fine particles ($PM_{2.5}$), BC, ultrafine particle counts provide a reasonably complete characterization of diesel exhaust levels.

The available epidemiologic evidence on the health effects of diesel exhaust goes back to the 1990s but the studies are challenging to interpret because exposures are not precisely quantified. Further, the studies were conducted in occupational settings and on healthy adult male workers, therefore the levels of exposure are above the range observed in the community setting and must be extrapolated with some uncertainty to women, children, and the elderly. Although no federal air quality standard for BC or diesel particulate matter exists, the health hazard is recognized (Health Effects Institute, 2015). The health endpoint of regulatory concern has been lung cancer and risk assessments are based on lifetime exposure scenarios. However, the U.S. EPA and the World Health Organization have withdrawn their previously published unit risk estimates, ostensively because the most appropriate metric to represent diesel exhaust exposure remains unknown. $PM_{2.5}$ elemental carbon (EC) has been used as a surrogate to date, but it is not expected that EC itself is the toxicologically active agent. In 2010 and again in 2016, the Oregon Air Toxics Science Advisory Committee (ATSAC) reviewed the available literature on diesel particulate matter and recommended an Ambient Benchmark Concentration (ABC) of 0.1 $\mu g/m^3$ (equivalent to 100 ng/m^3) which is very close to these previous risk estimates of the EPA and WHO, and assumes 70-year exposure duration and risk of 1 excess cancer in 1 million persons. This ABC was adopted by the Oregon Environmental Council in 2017, and provides a point of reference for evaluating potential health risk.

The possible effects of exposure to BC on neurodevelopment and cognition in school children have also been the subject of recent research efforts in Europe and the U.S (Basagana et al. 2016; Harris et al. 2016; Forns et al. 2017). These studies are motivated by the observation of translocation of ultrafine and fine particles from the lungs to the central nervous system in animal toxicology studies (Elder et al. 2006). The BREATHE Program in Barcelona, Spain followed 2,687 children in 265 classrooms in 39 schools, assessing attention with a computer-administered neurobehavioral test. Classrooms in these

schools are naturally ventilated and the penetration of outdoor $PM_{2.5}$ and NO_2 to the schools' indoor areas is high (Amato et al. 2014), and means that school children are exposed to elevated levels throughout the school day, indoors and outdoors. In the Barcelona classrooms, the mean NO_2 level was 15.8 ppb (11.9-18.9 ppb interquartile range) and the mean $PM_{2.5}$ elemental carbon was 1270 ng/m^3 (980-1240 ng/m^3 interquartile range). EC is measured using a thermal-optical transmittance, and BC is measured by optical reflectance - aethelometer. The BC:EC correlation is approximately 3:1 and varies with the source of soot emissions (Jeong et al. 2004). Converting the Barcelona EC values to BC yields 3810 ng/m^3 (2940-3720 ng/m^3 interquartile range). In another BREATHE publication, Sunyer et al. (2017) reported lower performance on attention tests for school children in the top exposure quartile of daily classroom EC and NO_2 relative to those in the bottom exposure quartile over a 12-month period. Basagana et al. (2016) reported reductions in cognitive growth in working memory and attentiveness across quartiles of classroom $PM_{2.5}$, but these effects were not observed for EC or other measures of particulate matter. The most recent Barcelona publication by Forns et al. (2017) demonstrated that deficits in working memory and inattentiveness persisted over 3.5 years of follow-up and were associated with outdoor NO_2 and indoor (classroom) ultrafine particle counts, but not EC.

The Project Viva Cohort Study in eastern Massachusetts followed children from pre-birth to 8 years of age (Harris et al. 2016). Residence location was used to model exposure to outdoor BC and $PM_{2.5}$. Children with higher mid-childhood exposure to BC and increased near-residence traffic density had greater problems with behavioral regulation as assessed by teachers, but no relationship was observed using parent report measures. The methods used in this report are similar to those of a 2008 analysis of Boston children (Fraco Suglia 2008). BC exposures were retrospectively estimated with a land-use regression model for 218 children in a cohort study for which neurocognitive assessments were available. BC was associated with decreased cognitive function across measurements of verbal and nonverbal intelligence, and memory.

In summary, the body of evidence for the independent effect of BC on cognitive development and function in children provides mixed evidence to support a causal hypothesis. The most reliable evidence comes from the Barcelona BREATHE Program which utilizes direct measurements of EC at schools, which is superior to the reliance on estimated exposure from land-use models used in other studies. The associations with cognitive deficits reported in the set of BREATHE papers suggests that traffic-related pollution as a whole is responsible for the observed neurodevelopmental effects. It is important to recognize that the schools and classrooms in the Barcelona studies rely on natural ventilation and indoor levels of pollutants are similar to those outdoors. In contrast, the HVAC system at Harriett Tubman Middle School effectively removes the fine particles and BC from traffic emissions and eliminates the hazard posed by sustained exposure to traffic air pollution throughout the school day.

3.4.2 HTMS Outdoor and Indoor Levels

The distributions of BC concentrations in outdoor air, and the supply and return air locations in the HVAC system are presented in Figure 5. Levels of BC in outdoor air were appreciably higher in the Fall 2018 monitoring period than during the Spring of 2019, with mean school-day concentration averaging 1399 ng/m^3 and an interquartile range of 757 to 1925 ng/m^3. In the Spring, mean school-day average BC

was 829 ng/m^3, with an interquartile range of 290 to 1127 ng/m^3. Thus, outdoor levels in both seasons exceeded the Oregon ABC. In both monitoring seasons, the HVAC system demonstrated large removal efficiencies for BC; approximately 95% in the Fall and 86% in the Spring. Very tight distributions of values were observed in the Spring for supply and return air, evidence of very good HVAC system performance.

In the Spring monitoring, BC was measured with a handheld aethelometer in the park and other outdoor areas surrounding the school, during lunchtime and afternoon hours. Median levels were comparable to those measured at the HVAC intake, ranging from 457 to 725 ng/m^3. The median neighborhood background level, measured several blocks to the east of the school, was 333 ng/m^3.

3.4.5 Implications for Health

The outdoor concentrations of BC at HTMS are within expected ranges, and resemble distributions of BC measured in recent years at Oregon DEQ monitoring sites in Portland (Figure 6). The distribution of one-hour BC concentrations at the Portland North Roselawn neighborhood site measured during 2010 to 2016 had a mean of 718 ng/m^3. At the Portland SE Lafayette over 10 months in 2010, a very similar distribution and mean of 745 ng/m^3 was observed. BC monitoring at the Tualatin I-5 near-roadway site over 2014 to 2016 averaged 1293 ng/m^3. In comparison, the Fall season outdoor average at HTMS was 1623 ng/m^3 and in the Spring was 829 ng/m^3. This comparison shows that outdoor levels of BC at HTMS are higher than residential neighborhood background levels in Portland, and are very similar to those measured at the DEQ near-roadway monitoring station, even though this DEQ site is a relatively long distance away in Tualatin.

Indoor BC exposure levels, as represented by return air concentrations, are very low, indicating a high level of protection for students and staff, with average school-day concentrations of 233 and 158 ng/m^3 in the Fall and Spring, respectively. While these indoor levels are higher than the 100 ng/m^3 ABC, they are within the uncertainty bounds of the risk estimate used to set this guideline, and the protection achieved by the HVAC system is very high. During the indoor time of the school day, students and staff experience lower exposures than they would likely receive in their homes or during commuting.

3.5 Ultrafine Particles

3.5.1 Relevant Background

As described earlier in Section 3.3, particulate matter (PM) is regulated in two size ranges, PM_{10} and $PM_{2.5}$. PM_{10} is the total mass of particles less them 10 micrometers (microns or μm) in aerodynamic diameter. Similarly, $PM_{2.5}$ is the mass of particles less than 2.5 μm in diameter. PM2.5 is also called *fine* particle mass. PM_{10} minus $PM_{2.5}$ gives the *coarse* particle mass. Ultrafine particles (UFP) represent that size fraction of particulate matter less than 0.1 μm in diameter. Because the individual particles in UFP have very little mass, other measures such as particle count and surface area have been used for toxicity testing in animal experiments.

Ultrafine particles are poorly soluble and when they deposit by diffusion they readily pass into epithelial tissues because of their tiny dimensions. If deposited in the nasal passages, these particles can translocate through the olfactory nerve into the brain. When deposited in the respiratory tract, UFP can pass via blood or lymph, where they can distribute to other organs of the body, such as the heart.

The physical and chemical properties of PM vary greatly, and toxicity of the mixture of particulate matter is determined by size, chemical composition, and solubility. This is a major source of variability in the effects for particulate matter, where mass is used as the metric of exposure. For example, the $PM_{2.5}$ mass contains the mass of the UFP fraction, but this mass is relatively small compared to the weight of particles in the $PM_{2.5} - PM_{0.1}$ fraction, and $PM_{2.5}$ mass does not accurately represent the presence of UFP. Thus, the use of particle counts to represent UFP exposure and dose has gained favor. Certainly, the application of a single set of federal air quality standards has practical advantages for monitoring and regulation, but the PM_{10} and $PM_{2.5}$ standards are acknowledged to have limitations for public health protection. Epidemiologic studies of the effects of UFP have only recently been conducted, and the evidence for independent health effects of UFP is limited (HEI Panel on the Health Effects of Traffic-Related Air Pollution, 2010; HEI Review Panel on Ultrafine Particulates, 2013; Weichenthal et al. 2017).

3.5.2 HTMS Outdoor and Indoor Levels

Figure 7 presents the distribution of ultrafine particle counts for outdoor air, and supply and return air points in the HVAC system. Mean UFP counts are averaged over the 9 AM to 4 PM school day. In the Fall, UFP counts averaged 24908 particles/cm^3, with an interquartile range of 17949 to 27170 particles/cm^3. The HVAC system removed these particles very efficiently; the average count in supply air was 1484 particles/cm^3 and the return air was 1067. A walking transect conducted inside the school yielded a mean count of 461 particles/cm^3 and an interquartile range of 264 to 498 particles/cm^3. Much lower counts were measured in outdoor air during the Spring monitoring period. The mean was 829 particles/cm^3, with an interquartile range of 290 to 1127 particles/cm^3. Particle filtration by the HVAC system continued to perform efficiently in the Spring, with mean supply air counts of 117 particles/cm^3 (interquartile range 62-151 particles/cm^3) and mean return air counts of 158 (interquartile range 107 to 156 ng/cm^3).

The PSU air monitoring team conducted walking transects in Lillis Albina Park and outdoor areas surrounding the school on two days in the Fall monitoring period and two days in the Spring. Particle counts were higher in the Fall than the Spring. A summary of the relative concentration magnitudes for Fall is presented below:

Location	Time	Ultrafine Particle Counts (median, particles/cm^3)	
		Wed Oct-10	Wed Oct-15
Park	Morning 8-9 AM	13,000	39,000
Park	Morning 9-10 AM	26,000	43,000
Lunch 1	Noon hour 11:15-12 PM	10,000	15,000
Lunch 2	Noon hour 12-12:45 PM	8,000	16,000
Park	Afternoon 1-2 PM	13,000	14,000

Dismissal on Flint Ave	Afternoon 3:30-4:15 PM	6,800	6,600
Neighborhood	Afternoon 4:15 & later	---	5,400

Two patterns are evident in this table. First, substantial day-to-day variation is observed. Second, UFP counts are highest in the morning hours on both days, and drop substantially by the first lunch period. This hourly profile may be attributed to reduced traffic emissions on I-5 as the morning rush hour ends, and because of warming atmospheric temperatures and increasing wind speed (Zhu et al. 2006). This outdoor pattern is evident in Figure 8 which presents the median UFP counts for the Spring monitoring period by outdoor location and time of day.

3.5.3 Implications for Health

Although air quality regulations currently do not address UFP, this class of submicron-sized particles may exert greater toxic effects compared with larger particle because of their greater surface area/mass ratio, chemical composition, deeper lung penetration, and ability to translocate to the systemic circulation and other organs. A recent workshop concluded that the current evidence base does not differentiate the effects of UFP from other particle size fractions and gaseous pollutants (Baldauf et al. 2016). The limited available epidemiologic literature focuses on adult respiratory and cardiac outcomes, and mortality. Studies considering children are beginning to be reported. For example, prenatal UFP exposure was associated with asthma onset by age 6 years in a recently published study from Ontario, Canada (Lavigne et al. 2019).

The lack of epidemiologic evidence and regulatory standards for UFP precludes a quantitative assessment of the health risks in the outdoor air surrounding the school. However, avoidance of sustained exposures to UFP counts exceeding 25,000/cm^3 seems advisable based on acute physiologic changes in blood pressure and micro-vascular function observed in exercising women exposed to high levels of traffic-related air pollution for short periods (Weichenthal, Hatzopoulou, and Goldberg 2014). While these physiologic changes are of uncertain health significance at this time, they do suggest the body is showing an oxidative stress response, and this would be expected to also occur in children.

UFP levels in the range of 25,000 particles/cm^3 were observed in outdoor areas surrounding Harriet Tubman Middle School during the morning hours of the Fall monitoring period. While the health risks of short-term exposures UFP are not known, and regulatory limits have not been established, sufficient toxicological and epidemiological evidence exists to recommend that outdoor physical education activities be scheduled in the later morning and afternoon when traffic pollution is much lower. This provides a margin of safety for students and staff who may be more sensitive to the adverse effects of traffic pollution (i.e., asthmatics).

3.6 Volatile Organic Compounds

3.6.1 Relevant Background

Volatile organic compounds are emitted as gases during combustion of gasoline and diesel fuels, and they are also emitted from indoor sources, including building materials and furnishings, office

equipment, and cleaning products. In fact, the concentrations of many VOCs are higher in indoor residential settings and public buildings, than outdoors (U.S. EPA Team Study, 1985). The health effects associated with exposure to VOCs include eye and upper airway irritation, asthma and allergic respiratory symptoms, headaches, dizziness, and nausea, memory impairment, damage to the liver, kidney and central nervous system, and for certain VOCs, cancer (Indoor Air Quality Scientific Findings Resource Bank, https://iaqscience.lbl.gov/voc-sensory). The charcoal bed filter bank in the HVAC system at HTMS is designed to remove broad classes of VOCs from outdoor air. There are hundreds of organic compounds, therefore a reduced set of VOCs with relevance to TRAP or high toxic potential were selected for monitoring by the PSU team, and were monitored in the outdoor air, and the supply and return air streams of the HVAC system.

Currently, no federal standards have been set for VOCs, although guidelines and recommendations have been set by various professional organizations (ACGIH, https://www.acgih.org/tlv-bei-guidelines/tlv-chemical-substances-introduction). The evidence for toxicity for VOCs that are commonly present in TRAP has been reviewed by the Air Toxics Science Advisory Committee (ATSAC) of the Oregon DEQ, and this advisory body has recommended Ambient Benchmark Concentrations (ABCs) for specific chemical compounds that were adopted by the Environmental Quality Commission of the State of Oregon in 2017 (https://www.oregon.gov/deq/aq/air-toxics/Pages/default.aspx). The ABCs are reviewed every 5 years and are based on the best available scientific evidence to derive an excess health effects risk (cancer, birth defect, organ damage) of 1-in-1 million from continuous inhalation exposure across a lifetime. This is the additional or extra risk of developing cancer due to exposure over the 70-year life of an individual. The ABCs include uncertainty factors to protect sensitive subgroups. Thus, the ABCs are health-based and provide a useful point of reference for evaluating population health risks, but it is incorrect to apply the ABCs to estimate the probability that an individual will experience an adverse health effect.

3.6.2 HTMS Outdoor and Indoor Levels

Levels of VOCs in the Spring monitoring period represent the typical occupancy conditions of the school without the influence of construction activities and off-gassing of new building materials. Outdoor air measurements of these VOCs at HTMS were less than concentrations reported by DEQ for Portland neighborhood monitoring stations (Figures 9-11). Using measurements of VOCs in the return air to represent the indoor exposure of students in classrooms, each of these VOCs were well below Ambient Benchmark Concentrations.

Chemical	Portland Background $\mu g/m^3$	Oregon DEQ ABC $\mu g/m^3$	Outdoor Air $\mu g/m^3$	Return Air $\mu g/m^3$
Benzene	0.59	0.13	0.10	0.00
Toluene	1.12	5000	0.41	0.18
m-, p-Xylene	1.28*	200*	0.31	0.10
o-Xylene	1.28*	200*	0.11	0.04
Ethyl-benzene	0.3	0.4	0.08	0.01

*mixed xylenes

3.6.3 Implications for Health

Indoor concentrations of VOCs were below the Oregon DEQ Ambient Benchmark Concentrations, indicating substantial protection while students and staff are indoors. Because students and staff are in this filtered air environment for the majority of their school day hours, their total daily exposure to VOCs is likely reduced relative to the total exposures they would receive when spending their day at their residence.

The potential for outdoor exposure to benzene during lunch and physical education activities exists. However, short-term exposures to benzene are not known to be associated with adverse health effects. Oregon DEQ monitoring indicates that outdoor levels of benzene are elevated across the Portland metro area and generally exceed the ABC. Human activities that emit benzene are common include evaporation from gasoline fuels at service stations and from vehicles, vehicle exhaust, and industrial processes. Control of benzene from these anthropogenic sources has been a focus of the Portland Air Toxics Solutions program (PATS). Additionally, natural sources of benzene in outdoor air include wildfires, which have impacted Portland urban air quality in recent years. The principal health concern for benzene is damage to the bone marrow and blood-forming tissues, and acute myeloid leukemia, resulting from long-term (lifetime) exposure.

4. Conclusions

- For each of the pollutants monitored, the filtered air delivered to the classrooms and interior spaces of the school is clean, safe and supportive of health for students and staff.
- Particle and gas removal by the HVAC system and its filtration systems remained consistently high across the school year.
- Outdoor levels of CO, NO_2, PM_{10}, and $PM_{2.5}$ were below federal air quality standards.
- Outdoor levels of pollutants associated with diesel exhaust (black carbon and ultrafine particles) were observed at elevated levels typical of locations near heavily travelled highways.
- Outdoor levels of traffic-related air pollutants are consistently elevated in the early morning hours, but drop substantially by the first lunch period at 11:15 AM.

5. Recommendations

- To provide a margin of safety for students and staff who may have asthma, or be sensitive to traffic-related air pollution, outdoor physical education activities should be scheduled in the later morning and afternoon hours to avoid the highest daily outdoor levels.
- To ensure the continued high and effective performance of the HVAC system, continued monitoring of outdoor, supply and return air should continue at 3-month intervals until the operating characteristics of this unique system is confidently understood. In addition to providing assurance of health protection, this data will allow definition of a schedule of filter replacement that minimizes cost and waste.

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Figure 1. Plots of the median concentrations of carbon monoxide across the 9 AM – 4 PM school day. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in parts per billion (ppb). The NAAQS is 9000 ppb averaged for 8 hours.

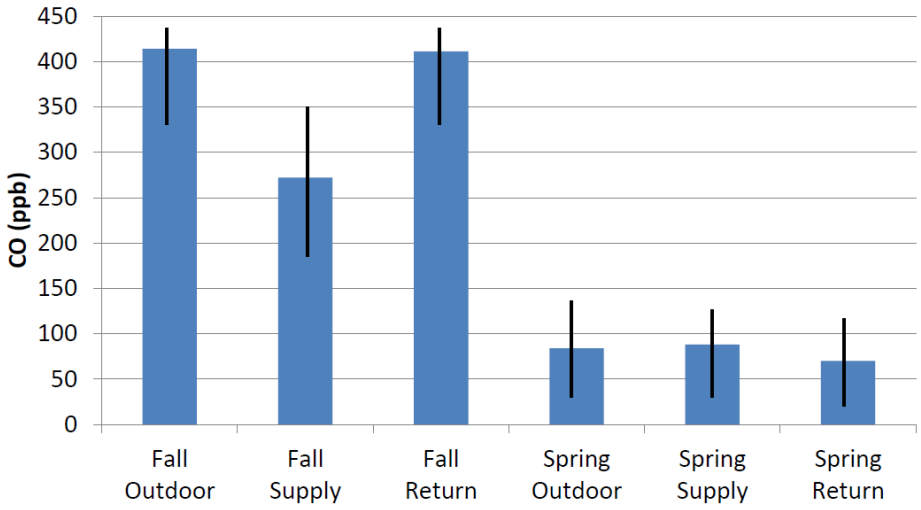

Figure 2. Plots of the median concentrations of nitrogen dioxide across the 9 AM – 4 PM school day. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in parts per billion (ppb). The NAAQS is 100 ppb averaged for 1 hour.

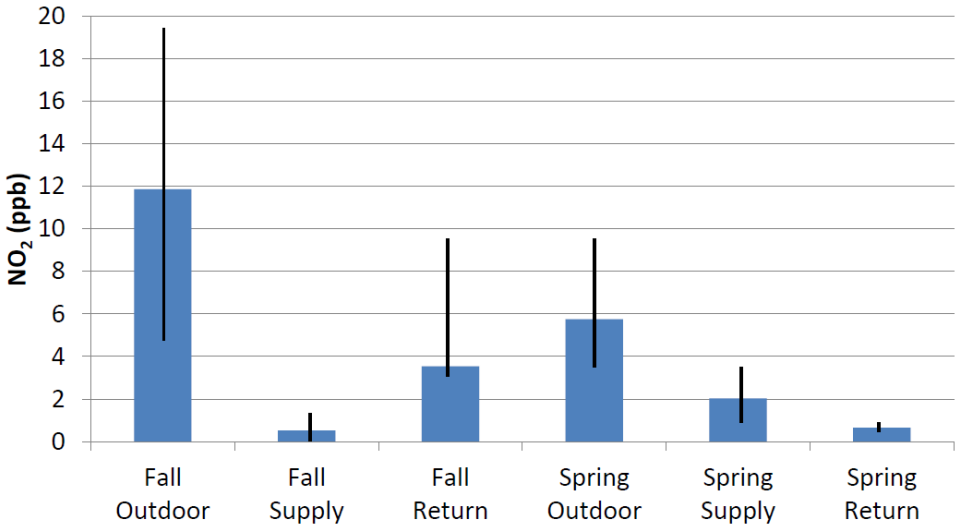

Figure 3. Plots of the median concentrations of PM_{10} across the 9 AM – 4 PM school day. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in micrograms per cubic meter ($\mu g/m^3$). The NAAQS is 150 $\mu g/m^3$ averaged over 24 hours.

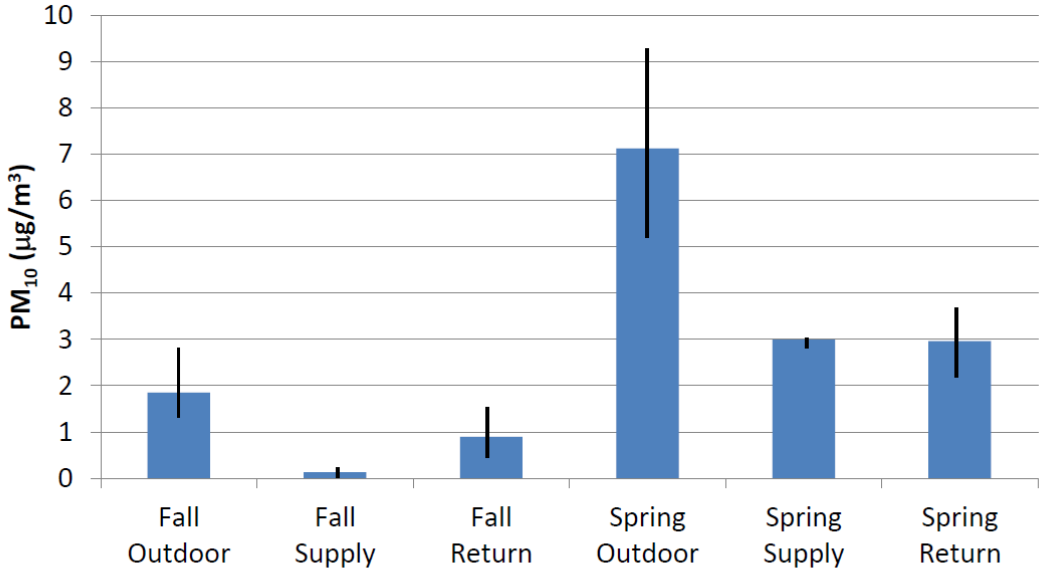

Figure 4. Plots of the median concentrations of $PM_{2.5}$ across the 9 AM – 4 PM school day. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in micrograms per cubic meter ($\mu g/m^3$). The NAAQS for $PM_{2.5}$ are 35 $\mu g/m^3$ 24-hour average and 12 $\mu g/m^3$ annual average.

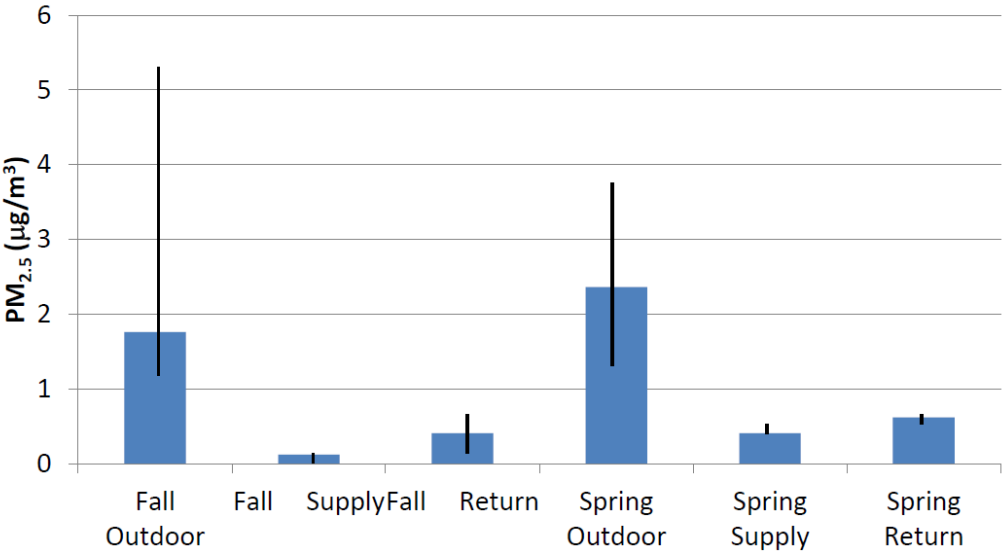

Figure 5. Plots of the median concentrations of Black Carbon across the 9 AM – 4 PM school day. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in nanograms per cubic meter (ng/m³). There is no federal standard for BC.

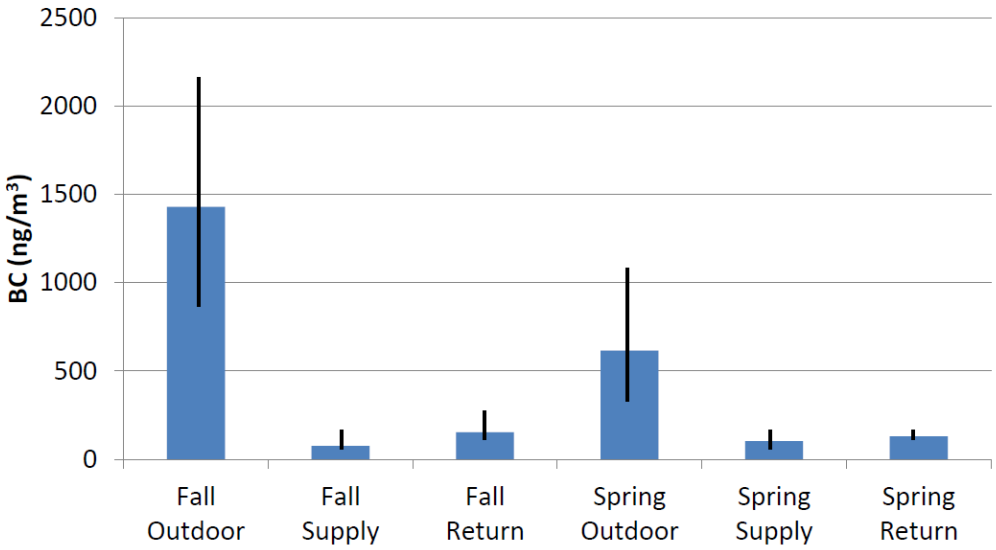

Figure 6. Plots of the distribution of one-hour average concentrations of Black Carbon measured at three Oregon DEQ monitoring sites (Portland N Roselawn 2010-16, Portland SELafayette 2010, and Tualatin I-5 Bradbury Court 2014-16). The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in nanograms per cubic meter (ng/m³).

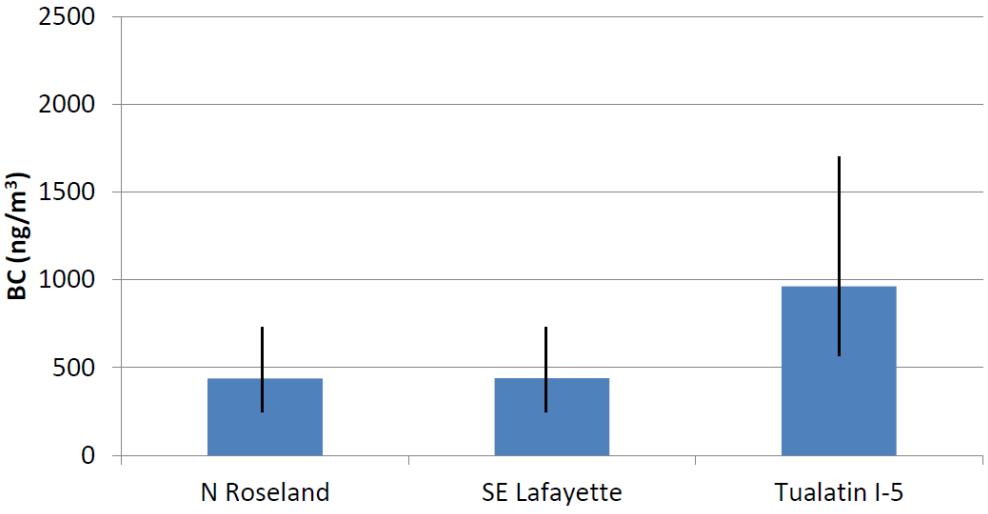

Figure 7. Plots of the median concentrations of Ultrafine Particles across the 9 AM – 4 PM school day. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in counts per cubic centimeter (particles/cm^3).

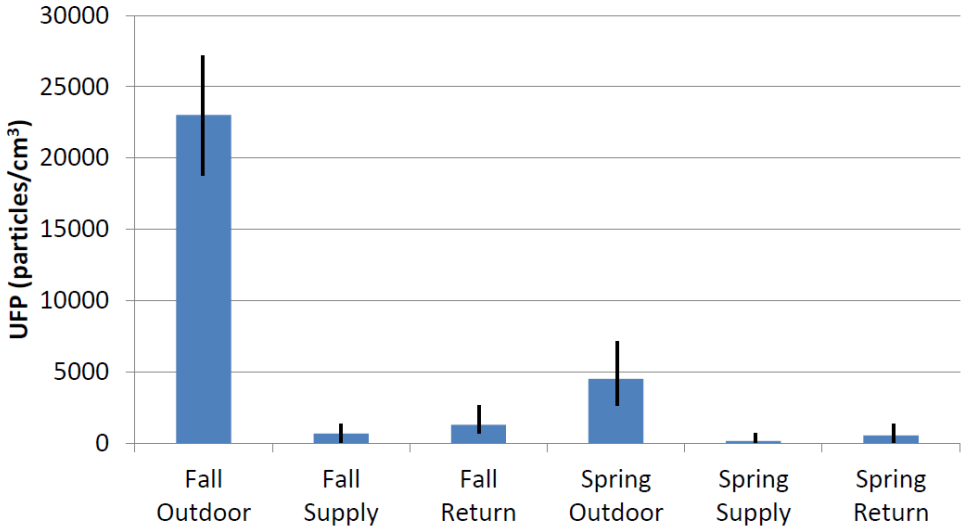

Figure 8. Plots of the median concentrations of Ultrafine Particles in outdoor areas surrounding HTMS in Spring 2019. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in counts per cubic centimeter (particles/cm^3).

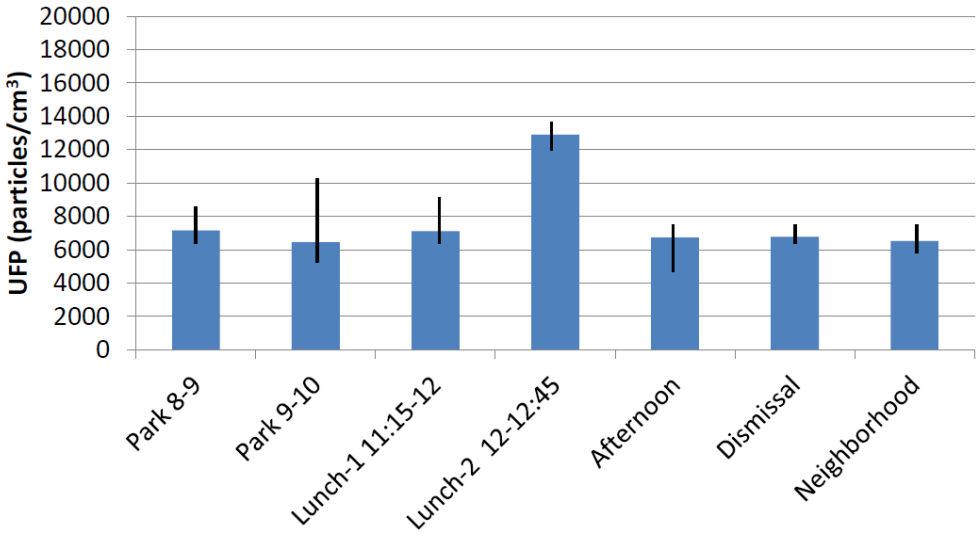

Figure 9. Plots of the median concentrations of the VOCs benzene and toulene in outdoor, supply, and return air locations of the HVAC system during Spring 2019. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in micrograms per cubic meter (µg/m³).

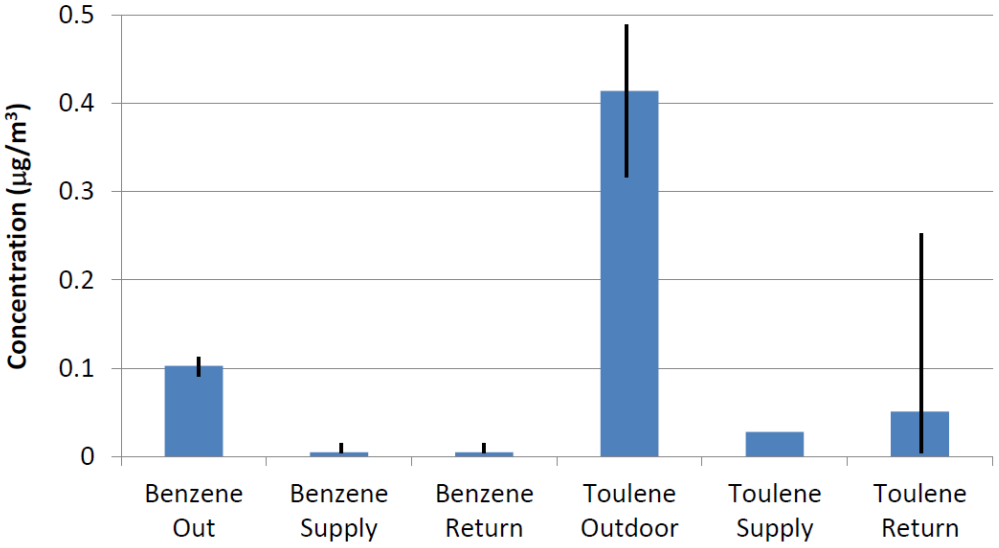

Figure 10. Plots of the median concentrations of the VOCs m-, p-Xylene and o-Xylene in outdoor, supply, and return air locations of the HVAC system during Spring 2019. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in micrograms per cubic meter (µg/m³).

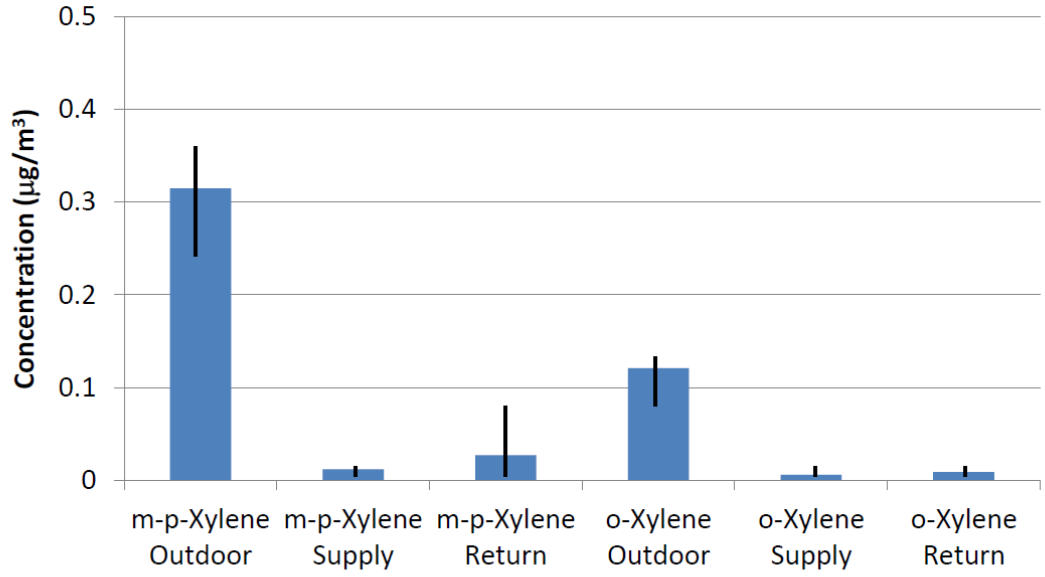

Figure 11. Plots of the median concentrations of the VOC ethylbenzene in outdoor, supply, and return air locations of the HVAC system during Spring 2019. The height of the solid bars represents the median concentration. The ends of the whiskers represent the 25th and 75th percentiles. Concentration is expressed in micrograms per cubic meter (µg/m³).