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Modeling Airflows and VOC Source Strengths for an Occupied School

by

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Modeling Airflows and VOC Source Strengths for an Occupied School

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1. Abstract

Volatile organic compounds (VOCs) are a group of air pollutants that can adversely impact human health, engage in chemistry indoors, and meaningfully degrade indoor and outdoor urban air quality. While extensive research with regard to VOC emission rates from indoor sources has been conducted, it was not until recently that this work began to focus on characterizing emissions from humans and human activity in depth. As buildings are constructed to be increasingly airtight, and the materials utilized are chosen to reduce VOC emissions, it follows that human contributions are poised to become increasingly important indoor sources of VOCs. Utilizing data extracted from a three-month campaign conducted at Harriet Tubman Middle School in Portland, Oregon, this study modeled airflows through the school and quantified source strengths for VOCs over the course of two days. Emission rates for seven compounds that are traditionally associated with human metabolism and activity were calculated, as were source strengths for BTEX compounds (benzene, toluene, xylenes, and ethylbenzene), which are typically associated with traffic-related air pollution (TRAP). In terms of per-person VOC emission rates, it was found that the values determined for some of the chosen compounds were in close agreement with the limited literature that exists on the subject, and that some varied greatly, likely due to differences in the buildings themselves, the occupants and their activities, and dissimilar experimental designs across studies. In terms of BTEX compounds, source apportionment revealed that the majority of their presence was due to supply air, which was expected considering the elevated levels of outdoor TRAP constituents in the near-roadway building. Comparing source apportionment percentages of BTEX compounds to another study that took the same approach, similar distributions were found—an outcome that suggested that despite the school's proximity to a roadway and elevated outdoor BTEX levels, the air-cleaning system was effective.

2. Introduction

As humans spend nearly 90% of their time indoors,¹ a heightened awareness of sustainable building design, improved indoor air quality, and effective air-filtration has emerged. Volatile organic compounds (VOCs)—which are defined as any compound of carbon (with a few notable exceptions, such as carbon monoxide and carbon dioxide) that participates in atmospheric photochemical reactions—are emitted from thousands of consumer products, as well as from human metabolism² and internal combustion engines in vehicles. Long-term indoor exposure to VOCs can cause impaired cognition³ and detrimental health effects to varying degrees,⁴ depending on the nature of the compound in question and the level at which it is concentrated. Because these pollutants have such direct consequences for humans, it is important to understand exposure concentrations and to investigate the means by which they enter into enclosed spaces. This study aimed to quantify emission rates for two groups of VOCs for two different purposes, each meant to gain further insight into the fluid dynamics that characterized the unique field site at which data was taken.

Harriet Tubman Middle School is an institution built in close proximity to I-5, a heavily trafficked roadway in Portland, Oregon. This seven-lane highway is used by upwards of 120,000 vehicles a day and is located a mere 20-125 meters from the school.⁵ Circumstances such as these are far from an anomaly: 40% of urban populations live within 300-500 meters of a major highway or road⁶ and 15% of schools, or about 6.4 million children, are less than 250 meters from a highway.⁷ Exposure to traffic-related air pollution (TRAP) has been proven to be a source of health-related issues for humans—particularly for vulnerable populations, such as children.⁸ Moreover, an element of racial patterning emerges with regard to TRAP exposure, as schools with a majority African-American student body, such as Harriet Tubman Middle School, are more likely to be located near busy roadways.⁷

In Fall 2018—after having been closed since 2012 due to a decrease in enrollment—Harriet Tubman Middle School was reopened with a renovated HVAC system. This system was outfitted with MERV8 and MERV16 high-efficiency particle filters and an activated carbon gas-phase air cleaning mechanism, and additionally, the building envelope was redesigned to reduce outdoor air infiltration.⁹ Portland Public Schools selected Portland State University to investigate the air-handling system's effectiveness over the course of three, six-week long phases. Phase I, which began in February 2018, assessed outdoor air quality prior to the air-handler's installation. Phase II, which began in September 2018, monitored air quality throughout the school, shortly after the air-handler's installation. Phase III, which began in May 2019, used the same approach as Phase II, but after eight months of the air-handler being operated on weekdays between 06:00 and 18:00. The majority of the data utilized in the subsequent analysis was taken from measurements made during Phase III.

While the primary focus of the campaign was to verify and report back to Portland Public Schools the efficiency of the enhanced HVAC system, the nature of the data collected made it suitable for use in adjacent investigations. Focusing on two days during Phase III of the campaign—May 27, 2019, a holiday in which the air-handler was operating but the school was mostly vacant, and May 28, 2019, a weekday in which the air-handler was operating and the school was fully occupied—allowed me to model airflows through the school and calculate VOC

emission rates that were apportioned by their source. The investigation of an unoccupied day was carried out intentionally in order to account for non-occupancy related VOC sources, such as furniture and building materials. These values would be subtracted from total indoor emission rates to arrive at per-person quantities. The analyzed data was interpreted in two different manners:

Per-person VOC emission rates

First, my goal was to quantify per-person VOC emission rates throughout the school, concentrating primarily on particularly volatile compounds associated with either human metabolism or human activity. While much of the practical research surrounding VOCs has focused on reducing emission rates in building materials and limiting outdoor infiltration in newly designed buildings, few studies have explored the implications of human emissions. As buildings continue to be constructed with VOC reduction in mind, the majority of indoor VOC emissions will inevitably be attributed to humans and human activity.

Three studies in particular served as inspiration for mine, following similar approaches, though carrying them out under much different circumstances: Tang et al., 2016,¹⁰ which measured VOC emission rates over the course of two weeks in a university classroom setting, Stönnner, 2018,¹¹ which measured per-person VOC emission rates in both children and adults in a crowded cinema, and Pagonis, 2019,¹² which measured VOC emission rates over the course of six weeks at a university art exhibit. The limited literature on this specialized subject created for me a unique opportunity; I was able to compare my results directly to the few sets of data that had previously been published, accepting that my work was a contribution to an area of study that is at the outset of being explored.

Traffic-related air pollution—BTEX compound source strengths

Where the first group of VOCs I chose to examine were related to human activity, the unusual setting at which the field study took place inspired me to also focus on a group of compounds associated primarily with TRAP: benzene, toluene, xylenes, and ethylbenzene (BTEX compounds). These compounds are known to contribute to the formation of ozone and smog, and sustained exposure to them can lead to human health issues.¹³ A primary source of BTEX emissions is exhaust from vehicles, and thus Harriet Tubman Middle School's proximity to I-5 poses obvious risks for students. Buildings require outdoor air to be brought into them by an HVAC system, and this outdoor air is often assumed to be clean; in this scenario this is not a safe assumption to make. Previous studies demonstrate that levels of outdoor air pollution at the site are elevated—absent air-cleaning, ventilation with outdoor air will introduce TRAP into the school.⁹

Laguerre et al., 2020,⁹ the investigation from which I retrieved my data set, served as the basis for my analysis of BTEX compounds. Monitoring supply air contributions into the school—which were a mixture of filtered outdoor and recirculation air—enabled me to compare source apportionment distributions of BTEX compounds to those of compounds associated with indoor activity, thus validating my characterization of airflows through the school. Additionally, I was

able to compare these source apportionments to a separate study¹⁰ conducted under similar circumstances, drawing conclusions about the effectiveness of the renovated air-handler.

In elevated concentrations, VOC exposure has the potential to negatively affect human health, and thus degraded indoor air quality is a phenomenon that must be actively avoided. Here, it is my intention to explore how a state-of-the-art air-cleaning system might affect levels of outdoor air pollutants within a building, while also taking into consideration indoor contributions from human metabolism, human activity, and non-human sources.

3. Materials and Methods

3.1: Site description

Figure 1: Schematic of Harriet Tubman Middle School and the renovated air-handler installed Fall, 2018. The volume of the building is $36,812 \text{ m}^3$ and the supply air change rate (λ_{SA}) through the school is 1.965 h^{-1} . λ_{RA} represents the air change rate of return air (h^{-1}), λ_{OA} represents the air exchange rate of outdoor air (h^{-1}), and λ_{EA} represents the air change rate of exhaust air (h^{-1}). The air-cleaning system was outfitted with MERV 8, MERV 16, and activated carbon filters.

Harriet Tubman Middle School (2231 N Flint Ave, Portland, OR 97227) is located in the northern part of Portland, Oregon, and in 2019 had an enrollment of 472 students with 33 faculty members, according to Portland Public Schools. Figure 1 presents a schematic of the institution, emphasizing the renovated HVAC system that was installed in Fall 2018 before the school's reopening.

Air was monitored at three locations in relation to the air-handler: Return air is representative of indoor air present throughout the school. Outdoor air is representative of conditions just outside of the school; this monitoring location accounts for the air before it is taken in from outside and cleaned. Supply air is composed of return and outdoor air after it passes through the air-handler for cleaning, just before it is to be pushed back into the school. Finally, though not explicitly considered in subsequent calculations, exhaust air (represented by λ_{EA} in Figure 1) accounts for air leaving the system in order to maintain neutral pressure.

The project's building contractor estimated that the air change rate through the school was approximately 40,000 – 60,000 cubic feet per minute (*cfm*), a metric that I ultimately used to confirm that my calculated air change rate was within reason.

3.2: Field deployment

The initial Harriet Tubman Middle School campaign utilized a combination of sophisticated instruments to monitor several types of contaminants, taking place over the course of more than a year. As previously stated, the dataset from which I extracted information from was limited to the six weeks that comprised Phase III—more specifically, two days from within this period—and the majority of the work that I completed was related to data analysis. For a more detailed description of the campaign's field deployment, consult Laguerre et al., 2020.⁹

During Phase III of the campaign, VOC sampling was conducted using a proton-transfer-reaction mass spectrometry (PTR-MS) instrument. Briefly, this method relies on the reaction of H_3O^+ ions, which fail to react in the presence of clean air but transfer protons to most common VOCs.¹⁴ VOC concentrations were sampled by use of a switching valve, which alternated between return air, outdoor air, and supply air in regular, ten-minute intervals. Additionally, four low-cost sensors (Onset MX1102) were used to measure temperature, relative humidity, and CO_2 concentrations. Further details concerning the instrumentation, sampling method, and analysis of data collected during the field campaign can be found in Laguerre et al., 2020.⁹

4. Calculations

4.1: Calculating outdoor air exchange rates

The first step in modeling airflows through the school involved calculating outdoor air exchange rates. Pursuing this near the beginning of the project was intentional—applying scientific principles to characterize airflow into and through the building was an essential part of being oriented to the experimental site. The project's building contractor communicated that the air-handler was in operation from 06:00 to 18:00 on weekdays and was non-operational on weekends; the goal was to see if this cycling process was observable in the data. If the air-handler were running on schedule and working correctly, I hypothesized that the outdoor air exchange rate would prove to be statistically, significantly higher on weekdays in comparison to weekends.

In order to do this, a tracer decay test was implemented using CO_2 . Time-series measurements of CO_2 were available for the majority of Phase III of the project and were examined between April 19, 2019 and June 19, 2019. To determine the most ideal periods of decay to investigate, CO_2 concentrations in *ppm* were plotted against time for each day, after which the most pronounced decay period was chosen for analysis. Due to the uncertainty associated with the CO_2 sensors, a lower limit of 450 *ppm* was enforced on the decay period data. For weekdays, the decay periods were chosen just after the air-handler was powered off, between 18:00 and 20:00; typical initial values were between 650 and 700 *ppm*. For weekends, when the air-handler was powered off for the entirety of the day, the decay period was analyzed between 09:00 and 15:00 and typical initial values were between 450 and 500 *ppm*. Assuming an outdoor CO_2 concentration of 420

$ppm, \ln \left(\frac{CO_{2,v} - CO_{2,OA}}{CO_{2,0} - CO_{2,OA}} \right)$ vs. relative time for the period of decay was plotted and a linear regression was performed in MATLAB to extract the air exchange rate in h^{-1} . Here, $CO_{2,v}$ is the variable CO_2 concentration, $CO_{2,OA}$ is the outdoor CO_2 concentration, and $CO_{2,0}$ is the CO_2 concentration at time zero. This process was employed for each day of the two-month period; a total of 30 weekdays and 11 weekend days were utilized. Outdoor air exchange rates that did not fall between $0.3 h^{-1}$ and $1.5 h^{-1}$ were considered outliers and excluded from the proceeding statistical analysis.

First, the outdoor air exchange rate data for weekdays and weekends were tested separately to ensure they were normal. Using a combination of MATLAB and Microsoft Excel, the Kolmogorov-Smirnov Test was performed on the data, yielding a weekday KS value of 0.08 and a weekend KS value of 0.14—both sets were determined to be normal. The details of this test can be found in *Appendix (A)*. Next, a student t-test was performed on the two datasets to determine whether or not they were statistically, significantly different. A p-value of 6.6×10^{-7} was returned, indicating that the two sets were. A box plot was constructed to demonstrate these findings:

Figure 2: Box plot of outdoor air exchange rates at Harriet Tubman Middle School between April 19, 2019 and June 19, 2019. Air exchange rates between $0.3 h^{-1}$ and $1.5 h^{-1}$ were excluded from the data set.

This first, crucial step provided confidence that the HVAC system was taking in outdoor air—essential for the well-being of occupants—and pushing it through the school at rates consistent with expectations for outdoor air ventilation, based on discussions with the building’s mechanical contractor. However, due to the uncertainty associated with selecting and analyzing weekend decay periods, a more robust approach to determining non-occupancy contributions was sought after. Thus, the focus of the study was narrowed to two days in which the air-handler operated during normal hours: May 27, 2019, a holiday when the school was vacant, and May

28, 2019, a day when the school was occupied. During the occupied day, the outdoor air exchange rate was found to be 0.8457 h^{-1} . This value was computed again using a different method later in the study, for it was vital to utilize two separate approaches in order to validate airflow characterizations. The outdoor air exchange rate found here was subsequently employed when calculating the number of people present in the school on May 28, 2019, which is explored further in *Section 4.3*.

4.2: Determining stable occupancy periods

Several calculations in this study required a stable occupancy period to be determined—a phenomenon that can be observed when the CO_2 concentration in return air has reached a stable level for a prolonged period of time. Periods that have this quality are typically observed between an accumulation period of students entering the school, which will be elaborated upon in *Section 4.4*, and a decay period in which students are leaving the school, which was used to calculate outdoor air exchange rates in *Section 4.1*.

Creating two plots in MATLAB (*Figure 3*)—one for May 27, 2019 and one for May 28, 2019—of return air CO_2 concentration vs. time, the data cursor tool was used to identify the beginning and ending points of a consistently stable period on May 28, 2019, the occupied day. The slope of this region of stable occupancy was found to be $0.1015 \frac{\text{ppm}}{\text{h}}$, indicating the chosen period's relative stability.

Figure 3: Return air CO_2 concentration vs. time plots for 05/27/19 and 05/28/19, used to assess periods of stable occupancy.

As expected, when the school was assumed to be mostly unoccupied and the air-handling unit was still in operation, CO_2 concentrations were generally much lower. As the school was vacant on May 27, 2019, a stable occupancy could obviously not be determined, and thus the same timeframe selected for May 28, 2019 was applied: 10:12 – 12:04. This decision was made primarily for the sake of consistency, but also in hopes of recognizing any diurnal processes, such as regularly scheduled cleaning events.

4.3: Calculating the number of people present on the occupied day: 05/28/19

Though Portland Public Schools reported that 472 students and 33 faculty members were enrolled or employed at Harriet Tubman Middle School in 2019, deviation from these numbers on any given day was expected to exist due to absenteeism, janitorial work, etc. Thus, a refined calculation of N —or the number of students and faculty present during the stable occupancy period based on CO₂ generation rates—was carried out.

Table 4 of Persily, 2017,¹⁵ which is considered to be an authoritative work on the subject, provided CO₂ generation rates in $\frac{L}{s}$ for humans based on their age, gender, and level of physical activity. Using *Table 3* from the same paper, an appropriate MET level for students of middle-school age was decided upon (1.4), as was an appropriate MET level for teachers and faculty (2.0). An age range of 11 – 16 was used for students, and instructors and faculty were divided evenly into three age ranges: 30 – 40, 40 – 50, and 50 – 60. Gender was divided equally into 50% male and 50% female for both subsets. CO₂ generation rates from Persily's *Table 4* were determined for each group, summed, and then divided by the idealized total number of people. See *Tables B(1)* and *B(2)* in *Appendix (B)* for more information on this matter. A CO₂ generation rate was arrived at for the school: $2.35 \frac{L}{s}$.

From here, the total CO₂ generation rate needed to be converted from $\frac{L}{s}$ to $\frac{mg}{h}$ and normalized by the idealized total number of people. In order to do this, a conversion factor had to be developed using the ideal gas law. Pressure was assumed to be equal to 1 *atm*, the ideal gas constant was assumed to be $0.08205 \frac{L \cdot atm}{mol \cdot K}$, and the temperature was averaged over the stable occupancy period and found to be 295.69 *K*.

$$Conversion\ Factor = \frac{1\ atm}{295.69\ K \cdot 0.08205 \frac{L \cdot atm}{mol \cdot K}} = 0.041218 \frac{mol}{L} \quad (Eq. 1)$$

Multiplying together the molar mass of CO₂ ($44.01 \frac{g}{mol}$), the conversion factor calculated above, and the CO₂ generation rate for the school in $\frac{L}{s}$ brought the generation rate into units of $\frac{g}{s}$. This value was then converted to hours and divided by 505—the number of occupants reported by Portland Public Schools—resulting in a weighted-average, per-person CO₂ emission rate of $30.4 \frac{g}{h \cdot person}$.

Finally, a flow balance equation was derived using CO₂ concentrations and the outdoor air exchange rate:

$$EF \cdot N = (CO_{2,RA} - CO_{2,OA})\lambda_{OA}V \quad (Eq. 2)$$

Here, EF is the CO₂ emission rate calculated prior to per-person normalization ($\frac{g}{h}$), N is the number of people present, $CO_{2,RA}$ is the return air concentration of CO₂ averaged over the stable occupancy period (*ppm*), $CO_{2,OA}$ is the concentration of CO₂ outdoors (assumed to be

420 ppm), λ_{OA} is the outdoor air exchange rate as calculated in *Section 4.1*, and V is the volume of the building (m^3).

Rearranging *Equation 2* for N and solving using values from the stable occupancy period on May 28, 2019 results in a total of approximately 448 people. This value will be used in *Section 4.6* when normalizing VOC emission rates by the number of people present.

4.4: Calculating the supply air change rate: 05/28/19

It was now imperative to shift focus to the supply air change rate, which was representative of the total airflow to the school after it had been treated by the air-handler. In order to accomplish this, both the region of pronounced CO_2 accumulation in return air that occurred each morning, as well as the stable occupancy period decided on in *Section 4.2* that immediately followed it, had to be utilized.

Using MATLAB's data cursor tool, along with the return air CO_2 concentration vs. time plot created to analyze the stable occupancy period on May 28, 2019 (*Figure 3*), the period of accumulation was determined: 09:05 – 10:11. The stable occupancy period directly following this, 10:12 – 12:04, is the same as the period determined in *Section 4.2*, and will be carried over into *Section 4.5* and *Section 4.6*.

Before proceeding to the next step, a correction factor had to be established in order to calibrate the deployed CO_2 sensors. In order to do this, both return and supply air CO_2 concentrations in the early morning hours (02:00 – 04:00), when the air-handler was expected to be off and the school to be unoccupied, were monitored. Dividing the average concentration of CO_2 in supply air by the average concentration of CO_2 in return air over this timeframe resulted in a correction factor of 0.90. The supply air CO_2 concentrations were then converted to $\frac{g}{m^3}$ and multiplied by 0.90, in order to adjust for the correction factor.

Additionally, return air CO_2 concentrations were modeled ideally using the following differential equation:

$$\frac{dCO_{2,RA}}{dt} = \lambda_{SA} CO_{2,RA} - \lambda_{SA} CO_{2,SA} + \frac{EF \cdot N}{V} \quad (\text{Eq. 3})$$

Due to the fact that multiple dependent variables were changing in time ($CO_{2,RA}$ and $CO_{2,SA}$), a discretized solution for *Equation 3* was calculated:

$$CO_{2,RA}^{t+\Delta t} = \left(\lambda_{SA} CO_{2,RA}^t - \lambda_{SA} CO_{2,SA}^t + \frac{EF \cdot N}{V} \right) \Delta t + CO_{2,RA}^t \quad (\text{Eq. 4})$$

Here, $CO_{2,RA}^{t+\Delta t}$ is the modeled return air CO_2 concentration at the previous time-step ($\frac{g}{m^3}$), λ_{SA} is the supply air change rate through the building (h^{-1}), $CO_{2,RA}^t$ is the modeled return air CO_2 concentration at the current time-step ($\frac{g}{m^3}$), $CO_{2,SA}$ is the corrected supply air CO_2 concentration

at the current time-step ($\frac{g}{m^3}$), EF is the school's per-person CO₂ generation rate in $\frac{g}{h \cdot person}$, as calculated in *Section 4.3*, N is the number of people present during the stable occupancy period, and V is the building volume.

The intention now was to use the Solver tool in Microsoft Excel to refine the λ_{SA} value in *Equation 4*. To do this, the squared error was computed using the difference between the experimentally determined and idealized model return air CO₂ concentrations. The sum of squared errors was then calculated over a series of timeframes that included the accumulation period and a variable period of stable occupancy directly following it. In order to converge on a number of minutes following the accumulation period to include, the Solver tool in Microsoft Excel—which will be discussed further below—was employed several times in intervals of five minutes until stability with regard to λ_{SA} was realized. λ_{SA} was then plotted against time, given in these five-minute intervals. Observing the plot included in the appendix (*Figure C(1)*), it is clear that λ_{SA} tends to converge to stability approximately 35 minutes after the end of the accumulation period. As a sanity check, the relative outdoor air exchange rate was plotted alongside the supply air exchange rate and compared to the value found in *Section 4.1*.

With the appropriate time interval in tow, the Solver tool in Microsoft Excel was employed with the objective set as the sum of squared errors (including 35 minutes of the stable occupancy period) and the changing variable cell set as λ_{SA} . The goal was to reduce the sum of squared errors, and thus the Solver tool was set to find a minimum, using the GRG non-linear method—the unconstrained variables were left non-negative. A supply air change rate through the school was returned: 1.965 h^{-1} .

4.5: Deriving equations for the unoccupied day: 05/27/19

Now that airflows through the school had been successfully modeled, it was time to turn to the study's main objective: determining VOC source strengths. Mass balance equations were taken from the supporting material that accompanied a prior study, Tang et. al., 2016,¹⁰ to help develop an approach from a similar investigation. In order to model VOC source strengths on May 28, 2019, it was imperative that data extracted from May 27, 2019—a day chosen because the school was assumed to be unoccupied, but the air-handler continued to run; it was Memorial Day—be analyzed first. Data obtained from this holiday allowed for the isolation of VOC emissions caused by non-occupancy sources, which could be subtracted from total indoor emissions on the occupied day in order to separate human contributions. It was assumed that the supply air change rate through the school would not be affected significantly by occupancy, and thus the same λ_{SA} value was utilized on both days.

Having established earlier in *Section 4.2* that the stable occupancy period found for May 28, 2019 would also be implemented on May 27, 2019 (10:12 – 12:04), an initial mass balance was constructed:

$$\frac{d(C_{RA})}{dt} = \lambda_{SA}C_{SA} + \frac{E(t)}{V} - \lambda_{SA}C_{RA} \quad (\text{Eq. 5})$$

Here, C_{RA} is the average return air concentration of a given VOC over the stable occupancy period ($\frac{g}{m^3}$), λ_{SA} is the supply air change rate through the school (h^{-1}), C_{SA} is the average supply air concentration of a given VOC over the stable occupancy period ($\frac{g}{m^3}$), $E(t)$ is the emission rate of a given VOC at time t , and V is the building volume.

Each term in *Equation 5* was multiplied by Vdt and then integrated over the stable occupancy period, t_i to t_f :

$$V \int_{t_i}^{t_f} d(C_{RA}) = \lambda_{SA} V \int_{t_i}^{t_f} C_{SA} dt + \int_{t_i}^{t_f} E(t) dt - \lambda_{SA} V \int_{t_i}^{t_f} C_{RA} dt \quad (\text{Eq. 6})$$

$$M = \int_{t_i}^{t_f} E(t) dt \quad (\text{Eq. 7})$$

Here, M represents the total mass emitted in terms of the time integral of the emission rate over the stable occupancy period. Solving *Equation 6* for $E(t)$ and substituting into *Equation 7* yields:

$$M = \lambda_{SA} V \int_{t_i}^{t_f} (C_{RA} - C_{SA}) dt + V \int_{t_i}^{t_f} dC_{RA} \quad (\text{Eq. 8})$$

The $\lambda_{SA} V \int_{t_i}^{t_f} (C_{RA} - C_{SA}) dt$ term in *Equation 8* represents net VOC removal due to ventilation, while the $V \int_{t_i}^{t_f} dC_{RA}$ term represents net VOC accumulation, both during the stable occupancy period. The C_{RA} and C_{SA} terms in the $\lambda_{SA} V \int_{t_i}^{t_f} (C_{RA} - C_{SA}) dt$ expression can be considered time averages over the stable occupancy period, multiplied by its duration (d_{SOP}). The integral in the $V \int_{t_i}^{t_f} dC_{RA}$ expression can be considered the difference between the final and initial return air concentration values over the stable occupancy period ($C_{RA,f}$ and $C_{RA,i}$, *Equation 9*). Accounting for these adjustments, the equation for total mass emitted can be rewritten as follows:

$$M = \lambda_{SA} V (C_{RA,avg} - C_{SA,avg}) (d_{SOP}) + V (C_{RA,f} - C_{RA,i}) \quad (\text{Eq. 9})$$

Total mass from supply air (M_{supply}) was calculated using the following equation:

$$M_{supply} = \lambda_{SA} V (C_{SA,avg}) (d_{SOP}) \quad (\text{Eq. 10})$$

With *Equations 9* and *10* derived, emission rates for the day in which the school was vacant (E_{vacant}) could be calculated with the following equation:

$$E_{vacant} = \frac{M_{vacant}}{d_{SOP}} \quad (\text{Eq. 11})$$

Here, M_{vacant} represents the total mass emitted for the vacant day. It should be noted that *Equation 9* was also implemented to calculate emission rates on May 28, 2019, but the variable $M_{occupied}$ was used to reflect the fact that the school was occupied.

4.6: Deriving equations for the occupied day: 05/28/19

Equipped now with all of the equations necessary to quantify VOC emission rates, *Equation 9*—as derived in *Section 4.5*—was employed to find $M_{occupied}$, or the total mass emitted on May 28, 2019. Substituting this value into *Equation 12* below, total indoor VOC emission rates were calculated:

$$E_{indoor} = \frac{M_{occupied}}{d_{SOP}} \quad (\text{Eq. 12})$$

Similarly, emission rates due to the contribution from supply air were calculated:

$$E_{supply} = \frac{M_{supply}}{d_{SOP}} \quad (\text{Eq. 13})$$

Finally, in order to account for contributions solely from humans, E_{vacant} was subtracted from E_{indoor} and divided by N , the number of people present on May 28, 2019 as calculated in *Section 4.3*:

$$E_{per-person} = \frac{(E_{indoor} - E_{vacant})}{N} \quad (\text{Eq. 14})$$

5. Results and Discussion

While Phase III of the Harriet Tubman Middle School campaign investigated well over 200 compounds—37 of which were confidently identified by their mass-to-charge ratio (m/z) and are explored further in *Appendix (D)*—for the purposes of this paper, only eleven were chosen to be investigated further. The first seven (isoprene, monoterpenes, acetone, formaldehyde, ethanol, methanol, and acetaldehyde) are all compounds known to be associated human activity. Isoprene and acetone are byproducts of human metabolism, while monoterpenes are commonly linked to human activities such as the application of personal care products and cleaning. Formaldehyde, which is admittedly difficult to quantify using a PTR-MS instrument,¹⁶ is often released from products such as furniture, building materials, and food, and is emitted in small quantities by humans. Ethanol, methanol, and other alcohols are known to be associated with the exhalation of human breath,¹⁷ and acetaldehyde is formed in the body due to the breakdown of ethanol. Furthermore, the analysis was conducted on 4 BTEX compounds (benzene, toluene, xylenes, and ethylbenzene—the latter of the two, as isomeric compounds, could not be distinguished by the PTR-MS instrument) that are associated with TRAP. Because these pollutants are not emitted by humans, their presence indoors is likely due to outdoor air ventilation and the infiltration of TRAP through doors, windows, and leaks present in the building. An additional criterion that was kept in mind when selecting VOCs to be investigated was their volatility; the compounds chosen needed to be volatile enough for us to rule out potential interference from the tubing

attached to the PTR-MS instrument. The VOCs selected here for in-depth analysis are volatile species, expected to have modest interaction with both the tubing and instrument itself. Prior studies conducted similar analyses with similar instrumentation on the same compounds, ultimately deciding to not explicitly account for tubing and instrument interference¹²—this informed my VOC selection process.

5.1: Noting VOC activity on occupied day: 05/28/19

Figure 4: Time-series data taken over the course of 05/28/2019 for temperature ($^{\circ}\text{C}$), relative humidity (%), carbon dioxide (ppm), isoprene (ppb), monoterpenes (ppb), and acetone (ppb). Solid lines represent readings and concentrations in return air and dashed lines represent readings and concentrations in supply air.

Figure 4 displays temperature ($^{\circ}\text{C}$), relative humidity (%), CO_2 (ppm), isoprene (ppb), monoterpenes (ppb), and acetone (ppb), all as a function of time over the course of May 28, 2019. The solid lines represent readings from return air while the dashed lines represent readings taken from supply air. As the air-handler runs from 06:00 to 18:00 on weekdays, a rise in temperature and slight decrease in relative humidity was to be expected during hours of operation. As referenced in Section 4.2, CO_2 is a reliable indicator of occupancy and thus a sharp increase in CO_2 return air concentration between 09:00 and 16:00—the typical hours of a school day—followed by an extended period of relative stability, was also expected.

Isoprene, monoterpenes, and acetone also experienced anticipated rises during times of occupation, due to their association with human metabolism and human activity. The noticeable spike in isoprene concentration that occurs at 06:00 is likely due to the air-handler being turned

on, which may have caused an interfering compound to be emitted as the fans and other mechanical systems started up. Traces of interfering compounds could also have accumulated overnight in the smaller volume of the return air sections of the air-handler and found themselves suddenly sprung from their resting place; this was not considered to be an occupation-related event. As stated before, both isoprene and acetone are present in human breath, and thus their elevated levels between 09:00 and 04:00 are to be expected. The concentration of monoterpenes spikes noticeably mid-afternoon and again shortly before the air-handler is turned off for the day. As monoterpenes are associated with personal care products, plants, fruits, and cleaning activities, the mid-day jump could potentially be explained by the commencement of lunch period, or a reapplication of personal care products following gym period. Furthermore, the evening spike could be explained by nightly cleaning activities; an on-site researcher noted that these took place each weekday around 17:00. Acetone appeared to accumulate overnight and was then flushed out at 06:00 when the air-handler turned on. Due to the fact that I was not physically present to note sudden shifts in human activity, I had to rely solely on the literature for guidance; the above explanations for concentration spikes have been speculated on in previous research.

5.2: VOC emission rates

While a complete table of the 37 VOCs that were identified are documented in *Appendix (D)* of this paper, *Table 1* below presents total indoor emission rates (E_{indoor}), supply air emission rates (E_{supply}), non-occupancy emission rates (E_{vacant}), and per-person emission rates ($E_{per-person}$), for the eleven compounds chosen for further investigation. All quantities are given in $\frac{mg}{h}$ with the exception of $E_{per-person}$, which is presented in $\frac{\mu g}{h \cdot person}$.

Table 1: Total indoor (E_{indoor}), supply air (E_{supply}), non-occupancy (E_{vacant}), and per-person ($E_{per-person}$) VOC emission rates for the 11 compounds chosen for further investigation.

<i>Compound</i>	$E_{indoor} (\frac{mg}{h})$	$E_{supply} (\frac{mg}{h})$	$E_{vacant} (\frac{mg}{h})$	$E_{per-person} (\frac{\mu g}{h \cdot person})$
Isoprene	58.6	21.5	19.6	87.1
Monoterpenes	119	14.7	18.4	225
Acetone	256	217	80.3	392
Formaldehyde	68.7	83.7	52.9	35.1
Ethanol	305	66.9	4.1	673
Methanol	599	613	407	430
Acetaldehyde	649	438	358	651
Benzene	10.3	28.8	5.3	11.1
Toluene	33.1	57.4	26.0	15.9
Xylenes/Ethylbenzene	52.5	59.4	36.4	35.9

For CO_2 , a separate analysis was undertaken that took into the account the error associated with the Onset MX1102 sensors that were deployed. The supply air concentrations were corrected for using the methods outlined in *Section 4.4*, leading to a total indoor emission rate of $13240.9 \frac{g}{h}$ and a per-person emission rate of $29.6 \frac{g}{h \cdot person}$. A per-person CO_2 generation rate of $30.4 \frac{g}{h \cdot person}$

was arrived at using the approach detailed in *Section 4.3*, further confirming the validity of my process.

5.3: Per-person VOC emission rates

As was discussed previously, three other studies also seeking to quantify per-person VOC emission rates in public places served as an inspiration for mine: Tang et al., 2016,¹⁰ Stönner, 2018,¹¹ and Pagonis, 2019.¹² Experimental conditions varied substantially across each study and in the work reported here. First, Tang et al.’s study took place in a university classroom setting, with anywhere between 26 to 67 college-aged students present during a stable occupancy period. Stönner’s experiment took place at a cinema that held at any one time between 50 and 230 people, and was arranged to distinguish between VOCs emitted by adults and children. Finally, Pagonis, 2019 was conducted inside of a university art museum that nearly 300 people cycled through in the course of an evening. In contrast, in 2019 Harriet Tubman Middle School had 505 students and faculty enrolled or employed at their institution, with approximately 93% of them being children between the ages of 11 and 16. Additionally, the work of Tang, Stönner, and Pagonis was all confined to a relatively small space— 670 m^3 , 1300 m^3 , and 6000 m^3 , respectively—while mine tracked airflows through the entirety of a $36,812\text{ m}^3$ building. *Table 2*, which presents a comparison between my findings and theirs, conveys per-person VOC emission rates for the seven key compounds I chose to explore.

Table 2: Per-person VOC emission rates for select compounds associated with humans. Values from this study are compared with other notable studies on the subject.

<i>Compound</i>	Per-Person Emission Rates ($\frac{\mu\text{g}}{\text{h-person}}$)			
	<i>This Study</i>	<i>Tang et al.</i>	<i>Stönner et al. (Children)</i>	<i>Pagonis et al.</i>
Isoprene	87.1	162	95	105
Monoterpenes	225	187	189	16
Acetone	392	2800	333	873
Formaldehyde	35.1	N/A	426	N/A
Methanol	430	156	1136	N/A
Acetaldehyde	651	114	252	354
Ethanol	673	94.9	116	12300

Isoprene is relatively constant across each study, while acetone—the other compound associated with human metabolism—agrees closely with Stönner’s findings, perhaps due to the fact that both experiments were focused primarily on children. The monoterpenes emission rate calculated during my study aligned with both Stönner and Tang et al.’s, perhaps suggesting that similar cleaning protocol was enacted at each location. Notable outliers include the ethanol emission rate from Pagonis, 2019, which is explained in their report to be due to the excessive levels of alcohol that were consumed during the exhibit. As mentioned earlier, formaldehyde is difficult to measure using a PTR-MS instrument, and thus it is not surprising that only one of the other studies included it. A limitation inherent in all four studies should be noted: VOCs emitted due to human metabolism and human activity could not be distinguished; all values presented here are representative of total emission rates due to humans in the general sense.

5.4: VOC source apportionment

The underlying goal of this study, and often air pollution studies in general, is to apportion air pollutants to their sources in order to understand their individual levels of contribution in a space. I was afforded the opportunity to compare VOCs that are thought to be generated by humans and their activities to those that are thought to be present due to outdoor pollution—a stark difference in apportionment should have been, and was, apparent.

As stated before, Harriet Tubman Middle School is built in close proximity to a heavily trafficked roadway, and the risk of human exposure to elevated levels of BTEX compounds is high. I wanted to characterize the manner in which VOCs entered the building, and thus BTEX source strengths were parsed out into supply air, occupant, and non-occupant contributions. These values were then compared to the source apportionments of VOCs associated with human activity, such as isoprene, monoterpenes, and acetone.

Figure 5: Source apportionment for VOCs related to human activity compared to BTEX compounds presented as percentages of contribution from supply air, occupant, and indoor non-occupancy sources.

It is evident from *Figure 5* that for VOCs typically associated with human activity, with the exception of acetone, which is present in both vehicle exhaust and human metabolism, occupant contributions account for the highest percentage of apportionment. In contrast, it is clear that for BTEX compounds, supply air accounts for the highest percentage of apportionment, suggesting that TRAP is entering the school. Though Tang et al., 2016¹⁰ does not explicitly quantify source apportionment percentages, upon visual inspection of *Figure 2* from their report (which is included as *Figure E(1)* in the *Appendix*), the percentage distributions are quite similar to the distributions of *Figure 5*. As the university where Tang et al.'s experiment took place was not near a busy roadway, agreement in source apportionment suggests that the HVAC system recently installed at Harriet Tubman Middle School is reducing exposure to outdoor, gas-phase TRAP.

5. Conclusion

Advances in building science typically prioritize lowering VOC emissions from materials and improving ventilation infrastructure. Progress being made in these areas, in combination with facilities that are built to be more and more airtight, fails to account for the possibility that humans may become a primary source of indoor VOC emissions. While the three papers cited often throughout this report—Tang et al., 2016,¹⁰ Stönnner, 2018,¹¹ and Pagonis, 2019¹²—have made successful efforts to quantify per-person VOC emission rates, beyond their studies and mine, little literature exists on the subject. Not only was the work detailed in this literature carried out under markedly different circumstances, the nature of the experiments themselves render the concept of consensus around a value irrelevant. Humans emit VOCs at different rates, spaces are comprised of different materials, etc., and thus it may be more worthwhile to explore which conditions lead to which range of source strengths.

While outdoor air brought into an indoor environment is assumed to be clean, this is not always the case—investments in ventilation must take this fact into account. The campaign from which my data was extracted explored further what my source apportionment analysis merely scratched the surface of. Laguerre et al., 2020⁹ assessed the effectiveness of the renovated HVAC system, while proving that BTEX compounds were being removed from outdoor air before entering the school. Still, for the purpose of my study, indoor BTEX concentrations were expected to be elevated. A quick comparison to Tang et al., 2016¹⁰ suggests that the air-handler was doing its job despite the school's proximity to a roadway.

As was noted, my study's focus was narrowed to include only eleven compounds, selected from a set of hundreds that are potentially identifiable. Additionally, my analysis was limited to a two-day period, though nearly three weeks of usable data exists. Going forward, I intend to expand my dataset to include additional compounds, extend the period of the study to a minimum of two weeks, and account for surface partitioning phenomena. In general, there is much work to be done with regard to this subject matter; further contributions are essential to the advancement of building science.

Appendix

Appendix (A): Kolmogorov-Smirnov test results

The following figure conveys the results of a Kolmogorov-Smirnov probability test performed in MATLAB. The test was employed to verify the normalcy of outdoor air exchange rate data, both on weekdays when the air-handler was operating and weekends when it was not. The KS value of the weekday data was 0.08 and the KS value of the weekend data was 0.14.

Figure A(1): Kolmogorov-Smirnov test for outdoor air exchange rates on weekdays, when the air-handler was operational.

Figure A(2): Kolmogorov-Smirnov test for outdoor air exchange rates on weekends, when the air-handler was non-operational.

Appendix (B): Calculating the total CO₂ generation rate for Harriet Tubman Middle School

Table B(1) displays a breakdown of assumptions made about the number of people present in the school, their ages and genders, and their MET levels. This information was used to arrive at a CO₂ generation rate for the entirety of the school in $\frac{L}{s}$.

Table B(2) displays Tables 3 and 4 from Persily, 2017,¹⁵ which were used together to find MET levels and CO₂ generation rates based on the information collected in Table B(1). For children, a MET level of 1.4 was chosen because I assumed that for the majority of the day students would be seated doing schoolwork. As for teachers and faculty, a MET level of 2.0 was chosen for I assumed that they would be on their feet lecturing for the majority of the day.

Table B(1): CO₂ generation rates for Harriet Tubman Middle School using Persily's MET level method.

	# of People	MET Level	CO ₂ Generation Rate ($\frac{L}{s}$)	# of People · Generation Rate ($\frac{L}{s}$)
Students (Age 11-16, Male):	236	1.4	0.0048	1.1328
Students (Age 11-16, Female):	236	1.4	0.0041	0.9676
Adults (Age 30-40):	11	2.0	0.0076	0.0836
Adults (Age 40-50):	11	2.0	0.0077	0.0847
Adults (Age 50-60):	11	2.0	0.0077	0.0847
Total	505			2.3534

Table B(2): MET level breakdowns by activity and CO₂ generation rate breakdowns by age and gender as taken from Persily, 2017.

TABLE 3 Values of physical activity levels (M) from compendium ⁴¹

Activity	M (met)	Range
Calisthenics—light effort	2.8	
Calisthenics—moderate effort	3.8	
Calisthenics—vigorous effort	8.0	
Child care		2.0 to 3.0
Cleaning, sweeping—moderate effort	3.8	
Custodial work—light	2.3	
Dancing—aerobic, general	7.3	
Dancing—general	7.8	
Health club exercise classes—general	5.0	
Kitchen activity—moderate effort	3.3	
Lying or sitting quietly		1.0 to 1.3
Sitting reading, writing, typing	1.3	
Sitting at sporting event as spectator	1.5	
Sitting tasks, light effort (e.g. office work)	1.5	
Sitting quietly in religious service	1.3	
Sleeping	0.95	
Standing quietly	1.3	
Standing tasks, light effort (e.g. store clerk, filing)	3.0	
Walking, less than 2 mph, level surface, very slow	2.0	
Walking, 2.8 mph to 3.2 mph, level surface, moderate pace	3.5	

TABLE 4 CO₂ generation rates at 273 K and 101 kPa for ranges of ages and level of physical activity (based on mean body mass in each age group)

			CO ₂ generation rate (L/s)						
Age (y)	Mean body mass (kg)	BMR (MJ/day)	Level of physical activity (met)						
			1.0	1.2	1.4	1.6	2.0	3.0	4.0
Males									
<1	8.0	1.86	0.0009	0.0011	0.0013	0.0014	0.0018	0.0027	0.0036
1 to <3	12.8	3.05	0.0015	0.0018	0.0021	0.0024	0.0030	0.0044	0.0059
3 to <6	18.8	3.90	0.0019	0.0023	0.0026	0.0030	0.0038	0.0057	0.0075
6 to < 11	31.9	5.14	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0100
11 to <16	57.6	7.02	0.0034	0.0041	0.0048	0.0054	0.0068	0.0102	0.0136
16 to <21	77.3	7.77	0.0037	0.0045	0.0053	0.0060	0.0075	0.0113	0.0150
21 to < 30	84.9	8.24	0.0039	0.0048	0.0056	0.0064	0.0080	0.0120	0.0160
30 to <40	87.0	7.83	0.0037	0.0046	0.0053	0.0061	0.0076	0.0114	0.0152
40 to <50	90.5	8.00	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0155
50 to <60	89.5	7.95	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0154
60 to <70	89.5	6.84	0.0033	0.0040	0.0046	0.0053	0.0066	0.0099	0.0133
70 to <80	83.9	6.57	0.0031	0.0038	0.0045	0.0051	0.0064	0.0095	0.0127
≥80	76.1	6.19	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
Females									
<1	7.7	1.75	0.0008	0.0010	0.0012	0.0014	0.0017	0.0025	0.0034
1 to <3	12.3	2.88	0.0014	0.0017	0.0020	0.0022	0.0028	0.0042	0.0056
3 to <6	18.3	3.59	0.0017	0.0021	0.0024	0.0028	0.0035	0.0052	0.0070
6 to < 11	31.7	4.73	0.0023	0.0027	0.0032	0.0037	0.0046	0.0069	0.0092
11 to < 16	55.9	6.03	0.0029	0.0035	0.0041	0.0047	0.0058	0.0088	0.0117
16 to <21	65.9	6.12	0.0029	0.0036	0.0042	0.0047	0.0059	0.0089	0.0119
21 to < 30	71.9	6.49	0.0031	0.0038	0.0044	0.0050	0.0063	0.0094	0.0126
30 to < 40	74.8	6.08	0.0029	0.0035	0.0041	0.0047	0.0059	0.0088	0.0118
40 to <50	77.1	6.16	0.0029	0.0036	0.0042	0.0048	0.0060	0.0090	0.0119
50 to <60	77.5	6.17	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
60 to <70	76.8	5.67	0.0027	0.0033	0.0038	0.0044	0.0055	0.0082	0.0110
70 to <80	70.8	5.45	0.0026	0.0032	0.0037	0.0042	0.0053	0.0079	0.0106
≥80	64.1	5.19	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0101

Appendix (C): Determining time after accumulation period at which air change rates converge

In order to determine the supply air change rate through the school, an appropriate length of stable occupancy following the accumulation period had to be determined. This was accomplished by running Microsoft Excel's Solver tool in intervals of five minutes and determining when the supply air change rate converged onto a stable value. The outdoor air exchange rate, which was previously determined to be 0.8457 h^{-1} , was plotted to further confirm convergence.

Figure C(1): Plot of air change rates vs. time of steady-state period following accumulation. Upon visual inspection, values seem to converge around 35 minutes.

Table C(1): The supply air and outdoor air change rates after being passed through Microsoft Excel's Solver tool. Intervals of time following the accumulation period were chosen in blocks of five minutes. Air change rates appeared to converge around 35 minutes.

Time Following Accumulation Period (min)	Supply Air Change Rate (h^{-1})	Outdoor Air Exchange Rate (h^{-1})
5	1.610	0.694
10	1.636	0.705
15	1.789	0.772
20	1.861	0.802
25	1.894	0.817
30	1.984	0.855
35	1.965	0.847
40	1.956	0.843
45	1.938	0.836
50	1.912	0.825

Appendix (D): VOC emission rates

Table D(1) is a comprehensive collection of emission rates for VOCs that were able to be identified by their mass-to-charge ratios (m/z).

Table D(1): Total indoor (E_{indoor}), supply air (E_{supply}), non-occupancy (E_{vacant}), and per-person ($E_{per-person}$) VOC emission rates for an extended suite of compounds identified using the PTR-MS instrument.

Compound	$E_{indoor} (\frac{mg}{h})$	$E_{supply} (\frac{mg}{h})$	$E_{vacant} (\frac{mg}{h})$	$E_{per-person} (\frac{\mu g}{h \cdot person})$
Isoprene	58.6	21.5	19.6	87.1
Monoterpenes	119	14.7	18.4	225
Acetone	256	217	80.3	392
4-OPA	25.2	19.9	40.5	-34.0
6-MHO	-14.0	39.9	-31.7	39.4
Formaldehyde	68.7	83.7	52.9	35.1
Methanol	599	613	407	430
Acetonitrile	6.6	63.0	1.2	12.1
IPA Fragment Propylene	37.1	617	-49.7	194
Acetaldehyde	649	438	358	651
Formic Acid	244	317	274	-65.3
Ethanol	305	66.9	4.1	673
Butadiene	29.7	66.9	18.5	25.1
Acrolein	16.2	11.1	11.4	10.6
Acetic Acid	631	263	550	181
Isopropanol	59.3	38.4	48.5	24.2
Vinyl Chloride	13.5	38.5	9.9	8.0
MEK Tetrahydrofuran	81.2	112	69.9	25.1
Benzene	10.3	28.8	5.3	11.1
Vinyl Acetate	57.8	28.2	40.1	39.4
Ethyl Acetate	47.6	53.9	31.3	36.4
MTBE	47.5	115	28.7	42.1
Toluene	33.1	57.4	26.0	15.9
Dichloroethene	61.7	19.9	55.8	13.4
Methylmethacrylate	21.5	74.9	24.6	-6.8
Methyl Butyl Ketone	16.4	4.5	15.9	1.2
Styrene	11.7	5.3	7.3	9.9
Xylenes/Ethylbenzene	52.5	59.4	36.4	35.9
Chlorobenzene	12.1	25.9	8.3	8.5
Chloroform	1.9	70.5	1.7	0.4
Trimethylbenzenes				
Ethyltoluene	13.0	1.4	13.9	-2.0
Naphthalene	17.5	10.2	16.0	3.4
Trichloroethylene	8.4	8.2	6.0	5.3
Tetramethylbenzene	26.1	18.0	22.9	7.2

Dichlorobenzene	10.9	11.3	1.7	20.5
Tetrachloroethylene	1.9	6.7	1.3	1.3
Trichlorobenzene	1.6	13.0	0.9	1.5

Appendix (E): VOC source apportionment

Figure E(1) is taken from Tang et al.'s 2016 work on per-person VOC emissions, and presents source rates that are apportioned by occupant, supply air, and indoor non-occupant contributions. Though percentages are not explicitly stated, I was able to visually inspect and compare the source apportionments of the compounds I investigated with this figure.

Figure E(1): Figure 2 from Tang et al., 2016. Source rates are apportioned by occupant, supply air, and indoor non-occupant contributions.

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References

1. Klepeis, N. E. *et al.* The National Human Activity Pattern Survey. *Lawrence Berkeley Natl. Lab.* (2001).
2. Phillips, M. Method for the collection and assay of volatile organic compounds in breath. *Anal. Biochem.* (1997) doi:10.1006/abio.1997.2069.
3. Allen, J. G. *et al.* Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environ. Health Perspect.* (2016) doi:10.1289/ehp.1510037.
4. Logue, J. M., Mckone, T. E., Sherman, M. H. & Singer, B. C. Hazard assessment of chemical air contaminants measured in residences. *Indoor Air* (2011) doi:10.1111/j.1600-0668.2010.00683.x.
5. Gall, E. T. *Indoor and outdoor air quality at Harriet Tubman Middle School and the design of mitigation measures: Phase I report.* (2018).
6. HEI. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects. *A Spec. Rep. Institute's Panel Heal. Eff. Traffic-Related Air Pollution; Heal. Eff. Inst.* (2010).
7. Kingsley, S. L. *et al.* Proximity of US schools to major roadways: A nationwide assessment. *J. Expo. Sci. Environ. Epidemiol.* (2014) doi:10.1038/jes.2014.5.
8. Rivas, I., Querol, X., Wright, J. & Sunyer, J. How to protect school children from the neurodevelopmental harms of air pollution by interventions in the school environment in the urban context. *Environ. Int.* (2018) doi:10.1016/j.envint.2018.08.063.
9. Laguerre, A., George, L. A. & Gall, E. T. High-Efficiency Air Cleaning Reduces Indoor Traffic-Related Air Pollution and Alters Indoor Air Chemistry in a Near-Roadway School. *Environ. Sci. Technol.* (2020) doi:10.1021/acs.est.0c02792.
10. Tang, X., Misztal, P. K., Nazaroff, W. W. & Goldstein, A. H. Volatile organic compound emissions from humans indoors. *Environ. Sci. Technol.* (2016) doi:10.1021/acs.est.6b04415.
11. Stönnner, C., Edtbauer, A. & Williams, J. Real-world volatile organic compound emission rates from seated adults and children for use in indoor air studies. *Indoor Air* (2018) doi:10.1111/ina.12405.
12. Pagonis, D. *et al.* Time-Resolved Measurements of Indoor Chemical Emissions, Deposition, and Reactions in a University Art Museum. *Environ. Sci. Technol.* (2019) doi:10.1021/acs.est.9b00276.
13. Rad, H. D. *et al.* Levels and sources of BTEX in ambient air of Ahvaz metropolitan city. *Air Qual. Atmos. Heal.* (2014) doi:10.1007/s11869-014-0254-y.
14. Lindinger, W., Hansel, A. & Jordan, A. Proton-transfer-reaction mass spectrometry (PTR-MS): On-line monitoring of volatile organic compounds at pptv levels. *Chem. Soc. Rev.*

- (1998) doi:10.1039/a827347z.
15. Persily, A. K. & De Jonge, L. Carbon dioxide generation and building occupants. *ASHRAE Journal* (2017).
 16. Schripp, T., Fauck, C. & Salthammer, T. Interferences in the determination of formaldehyde via PTR-MS: What do we learn from m/z 31? *Int. J. Mass Spectrom.* (2010) doi:10.1016/j.ijms.2009.11.001.
 17. Fenske, J. D. & Paulson, S. E. Human breath emissions of VOCs. *J. Air Waste Manag. Assoc.* (1999) doi:10.1080/10473289.1999.10463831.