

RISK OF COVID-19 MOVEMENT AND EXPOSURE ON PASSENGER RAILCARS:
ASSESSMENT OF AEROSOL TRANSPORT AND RAILCAR VENTILATION SYSTEMS

by
Kelsey R. Babik, MPH

A thesis submitted to Johns Hopkins University in conformity with the requirements for

the degree of Master of Science

Baltimore, Maryland
June 2021

© 2021 Kelsey R. Babik
All rights reserved

ABSTRACT

We conducted a series of static and dynamic experiments in a fleet of passenger railcars and locomotives for a large-scale, mass-transit company to measure the: (1) aerosol concentrations corresponding to respirable-sized/viral aerosols; (2) aerosol removal rates; and (3) air changes per hour (ACH) provided by the existing air handling systems. We evaluated the ventilation and air filtration (HVAC) systems effectiveness in a range of representative conditions to assess exposure risk. The risk of exposure to SARS-CoV-2 was assessed: (1) under standard conditions; (2) using minimum reported efficiency value (MERV) filters with increased filtration ratings; and (3) in the presence of a high-efficiency particulate-absorbing (HEPA)-scavenging system.

The engineering controls evaluated included: (1) recirculated to fresh air ventilation ratio; (2) MERV filters filtration efficiency; and (3) use of an air purifier. Aerosols were generated in the 0.3–5.0 μm size range using a Collison Nebulizer. Real-time aerosol concentrations were measured at multiple locations using photodetector particle counters. The ACHs and removal rates were calculated using log-linear regression. An analysis of variance was used to compare the particle concentrations under the different experimental conditions while a multiple linear regression was used to identify which engineering control(s) impacted the particle concentrations. The risk of exposure was estimated using an approach developed by Miller et al.

The recirculated to fresh air ratio had a minimal effect on particle air concentrations and on particle removal rates. The higher efficiency MERV13 filters significantly reduced particle concentrations ($p < 0.05$) and significantly increased particle removal rates ($p < 0.01$) compared to MERV8 filters. Compared to standard conditions, MERV13 filters reduced the exposure risk by 42%. Use of a HEPA-scavenger with a MERV13 filter causes a further reduction in risk (by 50%). The risk of exposure in the engine locomotives was much lower than in the passenger railcars due to much higher ACH values.

These results show that a simple upgrade in the efficiency of the HVAC filters results in reductions of particle concentration and risk of exposure in public-transit vehicles. Widespread upgrading of HVAC filter

efficiency in public-transit vehicles could reduce community-spread infectious respiratory diseases, protect transit workers, and slow disease spread.

Primary Reader and Advisor: Gurumurthy Ramachandran

Secondary Reader: Meghan Davis

ACKNOWLEDGMENTS

The completion of my thesis would not have been possible with the help of my advisor Dr. Gurumurthy (Ram) Ramachandran, my lab mate Darpan Das, and the engineers and facility support shop workers at the Amtrak Ivy City Maintenance Facility in Washington, DC including Tom Huffman, Karan Kothari, Gary “Bridges” Bridgforth, Eddy Holmes, Ricky Babbitt. I literally would not have been able to do this work without those gentlemen. Thank you.

I am also extremely grateful to Dr. Meghan Davis who extended a great amount of encouragement and support in completing and editing this work.

I would like to also extend my sincere thanks to all those who provided me with their guidance and mentorship as I completed this program, particularly Drs. Thomas A. Burke, Mary A. Fox, Jennifer D. Roberts, and Carissa Rocheleau.

I am also grateful to my fellow classmates and cohort members for their advice, support, and comradery, especially Emma Moynihan and Veronica Wallace who spent countless hours and cups of coffee working alongside me.

A special thanks goes to my friends and family who saw very little of me these last few years but who knew I still thought of them every day, particularly my parents Carol and Ron, my brother Luke, my Aunt Sue and Uncle Dave, and my dear friends Sam and Melissa.

Finally, I cannot begin to express my gratitude to my husband Eric and our dog Harley. Eric’s unwavering support and belief in me and Harley’s unconditional love and kisses were at times the only things that kept me going through this. I love you my boys!

DEDICATION

This thesis is dedicated to my parents and Norac for planting a love of science within me at an early age.

And to my teachers Mrs. Pessolano and Mrs. Ondrizek at St. Benedict School for fostering and cultivating that love and encouraging my curiosity.

I also dedicate this work to little girls with big dreams who are told that they aren't good enough, smart enough, or tough enough to make the things they want happen. You are enough.

Table of Contents

ABSTRACT..... ii

ACKNOWLEDGMENTS..... iv

DEDICATION..... v

LIST OF TABLES..... vii

LIST OF FIGURES..... viii

LIST OF EQUATIONS..... viii

1. INTRODUCTION..... 1

1.1 Background on mass-rail-transit vehicles heating, ventilation, and air conditioning (HVAC) systems..... 2

2. METHODS..... 4

2.1 Study design..... 4

2.2 Aerosol generation..... 6

2.3 Direct reading measurements..... 7

2.4 Data analysis..... 9

3. RESULTS..... 13

3.1 Size distribution generated by Collison nebulizer..... 13

3.2 Passenger railcars..... 13

3.3 Locomotives..... 18

3.4 Risk of exposure in passenger railcars and locomotives..... 19

4. DISCUSSION..... 21

REFERENCES..... 23

CURRICULUM VITAE..... 25

LIST OF TABLES

2.1	Railcar static sampling plan	5
2.2	Railcar dynamic sampling plan	5
2.3	Locomotives static sampling plan	6
3.1	ANOVA - Aerosol concentrations by sampling scenario under static conditions	14
3.2	Coefficients for ACH by aerosol size under static conditions	15
3.3	ANOVA - Aerosol concentrations by sampling scenario under dynamic conditions	16
3.4	Coefficients for ACH by aerosol size under dynamic conditions	17

LIST OF FIGURES

1.1	Layout of railcar	3
1.2	Layouts of diesel-powered locomotive (top) and electric locomotive (bottom)	3
2.1	Placement of HEPA scavenger unit in passenger car during dynamic tests	6
2.2	Pressured-air delivery system setup	7
2.3	Sampling instrument locations in passenger rail car	8
2.4	Location of measurements in the electric locomotive at the Engineer's and Assistant Engineer's seats	8
3.1	Distribution of count fraction per micrometer by particle diameter	13
3.2	Comparison of aerosol concentrations of particles across different experimental conditions during static testing in passenger railcars	14
3.3	Aerosol removal rates across all particle sizes using MERV13 and MERV8 filters	15
3.4	Comparison of aerosol concentrations across different experimental conditions during dynamic testing in passenger railcars	17
3.5	Comparison of aerosol concentrations of particles in different size ranges in the diesel-powered and electric-powered locomotives	18
3.6	Comparison of aerosol removal rates of particles in different size ranges in the diesel-powered and electric-powered locomotives.	19
3.7	Risk of infection distribution in a passenger railcar and in engine locomotives	19

LIST OF EQUATIONS

1.1	Air changes per hour (ACH)	3
2.1	Contaminant concentration in a well-mixed room at time t	10
2.2	Contaminant generation phase in a well-mixed room	10
2.3	Contaminant decay phase (purging) in a well-mixed room	10
2.4	Average concentration of quanta in a room	11
2.5	Probability (risk) of infection	12

1. INTRODUCTION

With the pandemic caused by the severe acute respiratory syndrome corona virus-2 (SARS-CoV-2), public transit in the US saw a dramatic reduction in usage, with some cities' ridership declining by as much as 90%¹ as commuters started working remotely, and leisure and business travel halted. Furthermore, as the science around SARS-CoV-2 evolved and it became clearer that the virus causing Coronavirus Disease-2019 (COVID-19) was transmitted via respiratory aerosols,²⁻⁴ studies asserting that public transit was a major vector for transmission^{5,6} prompted transit agencies to take measures to reduce the risk of exposure to SARS-CoV-2⁷⁻¹¹ and subsequently, reduce the risk exposure for passengers and for industry employees.

Industrial hygiene has long established that the most successful way to reduce exposure to aerosols of any kind is through increased ventilation.^{12,13} For SARS-CoV-2, the use of fresh air ventilation is ideal;^{3,14,15} however, this is typically not possible on high-speed trains. Therefore, the industry is left with ensuring that their ventilation systems are in top working order to control for exposure.

In partnership with a large-scale, interstate, mass-rail-transit company, we conducted a series of experiments in a fleet of passenger railcars and engine locomotives to assess the adequacy of the train's ventilation and filtration of the air handling systems to provide safe and clean air to passengers, transit employees, and to prevent community spread of COVID-19. Our objectives were to determine the effects of using a series of engineering controls on (1) the average particle number concentration in different size ranges corresponding to viral respirable aerosols; (2) the removal rate per hour of these aerosols; and (3) the estimated air change per hour (ACH) in a fleet of passenger railcars and engine locomotives under both static and dynamic conditions to evaluate the effectiveness of the ventilation and air filtration systems in a range of representative conditions and the risk of exposure. The engineering controls of interest included the:

1. Ventilation damper position (corresponding to the ratio of recirculated to fresh air);

2. Particle filtration efficiency of different minimum reported efficiency value (MERV) filters in the heating, ventilation, and air conditioning (HVAC) system;
3. Presence or absence of a presence of a high-efficiency particulate absorbing (HEPA) filter scavenging system.

1.1 Background on mass-rail-transit vehicles heating, ventilation, and air conditioning (HVAC) systems

1.1.1 HVAC system of railcar

The passenger railcars had 72 seats evenly spread over 18 rows with a central aisle, overhead compartments above each row, and two bathrooms on one end (Figure 1.1). Each car had a total volume of 5,314 ft³ with a designed fresh air intake flowrate of 1,200 cubic feet per minute (cfm) and a designed total supply airflow rate of 3,600 cfm. Thus, the air in the car was filtered approximately 40 times per hour (Equation 1.1) and replaced with fresh air 13 times per hour (Equation 1.1), according to design. Fresh air is brought into the car through dampers into the return air plenum, where it mixes with the recirculated air, passes through a MERV8 filter, then through heating and cooling elements into the supply air plenum and then back into the car. An exhaust blower removes a portion of the car air to the outside, and approximately 20% of the volume of the car is replaced with fresh air every minute. The cars were not airtight, and when in motion, the amount of fresh air entering the cars increased. Additionally, every time the doors opened at a station, the volume of air was mixed and any filtration of the passenger compartment from the HVAC system was lost. As designed, these cars can operate at speeds up to 125 mph (201 km/h).

Air changes per hour (ACH)

$$ACH = \frac{\text{total supply air or fresh air intake flow (cfm)} \times 60 \text{ min per hour}}{\text{volume of car (ft}^3\text{)}} \quad (\text{Eq. 1.1})$$

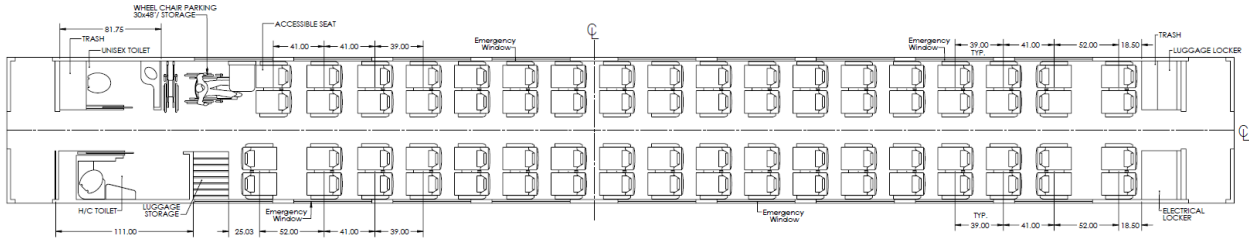


Figure 1.1. Layout of railcar.

1.1.2 HVAC system of engine locomotives

Two different engine locomotives were also assessed, an older, diesel-powered locomotive and a newer, electric-powered one (Figure 1.2). Each locomotive had three seats, one on the right for the engineer, on the left for the assistant engineer, and the third for the breakman or conductor, which was



Figure 1.2. Layouts of diesel-powered locomotive (top) and electric locomotive (bottom).

located behind the assistant engineer, typically folded up when not in use. Both types of locomotives had windows (one on each side) that slide open as well as a single

bathroom located in the front hood area of the locomotive. The approximate volume of the diesel-powered locomotive was 174 ft³ and the approximate volume of the electric-powered locomotive was 290 ft³. The designed air changes per hour for these locomotives (with an approximate usable volume of 417 ft³) were much higher than the passenger cabins (>25).

2. METHODS

2.1 Study design

The experiments in the passenger railcars were carried out under both static and dynamic conditions. Static conditions included evaluating the effectiveness of all three engineering controls while the train was at rest in the maintenance yard. Dynamic conditions, however, restricted our ability to evaluate all combinations of the engineering controls as these experiments were conducted as the train was moving, at an average moving speed between 73 and 85 mph, over approx. 300 miles. All experiments in the locomotives were done under static conditions. The total air ventilation rate through the car could not be changed.

The engineering controls of interest to be evaluated included:

1. Ratio of recirculated to fresh air via damper position (two positions reflecting ratios of 90:10 and 80:20 recirculated : fresh air)
2. Particle filtration efficiency of a MERV8 filter compared to that of a MERV13 in the HVAC. The default filter is a MERV8, with particle filtration efficiencies >20% and >70% for particles 1.0-3.0 μm and 3.0-10 μm , respectively, while the MERV13 has particle filtration efficiencies >50%, >85%, and >90% for particles 0.3-1.0 μm , 1.0-3.0 μm , and 3.0-10 μm , respectively.
3. Presence or absence of a HEPA air scavenging system (OmniAire 600V negative air machine with a flow rate of 150-550 cfm, 8" diameter exhaust collar, standard HEPA and MERV9 secondary filter).

2.1.1 Railcar static sampling

The sampling plan for the passenger railcars under static conditions is shown in Table 2.1. Standard operating conditions for this passenger car are reflected in sampling conditions 1 and 2. It is common for the damper positions to be changed (i.e. changing the ratio of recirculated : fresh air) under a variety of different circumstances (change in ambient temperature, traveling through urban vs rural areas, etc.) but it is not typical to change the efficiency of the HVAC filter nor employ the use of an air purifier/air scavenger system on the railcars.

Table 2.1. Railcar static sampling plan

Sampling Condition ID	Vent. Rate*	Vent. Damper	Filter Type	Air Purifier	# Experimental Runs	Notes
<i>Railcar - Static</i>						
AMFT1_01	ACH	Position 1 - Up	MERV8	N	3	done 3x times in 3 different cars
AMFT1_02	ACH	Position 2 - Down	MERV8	N	3	done 3x times in 3 different cars
AMFT1_03	ACH	Position 1 - Up	MERV8	Y	3	done 3x times in 3 different cars
AMFT1_04	ACH	Position 2 - Down	MERV8	Y	3	done 3x times in 3 different cars
AMFT1_05	ACH	Position 1 - Up	MERV13	N	1†	done 3x times in 3 different cars
AMFT1_06	ACH	Position 2 - Down	MERV13	N	1†	done 3x times in 3 different cars
AMFT1_07	ACH	Position 1 - Up	MERV13	Y	1†	done 3x times in 3 different cars
AMFT1_08	ACH	Position 2 - Down	MERV13	Y	1†	done 3x times in 3 different cars

* a fixed constant

† only one run for this scenario since MERV13 are not standard on cars in operation and concern of HVAC overload

2.1.2 Railcar dynamic sampling

The sampling plan for the passenger railcars under dynamic conditions is shown in Table 2.2. Given the constraints of a moving train, we could not change the damper position or the filter type. Even though changing the damper position is common in certain situations, it is not typically done during transit. Therefore, to capture the more realistic data possible, we did not change the damper position. Additionally, we were able to install the HEPA scavenger unit (Figure 2.1) and operate it at high and low fan speeds.

Table 2.2. Railcar dynamic sampling plan

Sampling Scenario ID	Vent. Rate*	Vent. Damper*	Filter Type*	Air Purifier	# Experimental Runs	Lentgh of Trip Leg (mi)	Average Total Speed (mph)	Average Moving Speed (mph)	Max Speed (mph)
<i>Railcar - Dynamic</i>									
AMFT1D_01	ACH	Position 1 (Up)	MERV 8	Y (high)	3	136	70	82	127
AMFT1D_02	ACH	Position 1 (Up)	MERV 8	Y (low)	3	96	64	85	127
AMFT1D_03	ACH	Position 1 (Up)	MERV 8	Y (high)	1	0†	48	69†	72†
AMFT1D_04	ACH	Position 1 (Up)	MERV 8	N	1	0†	48	69†	72†
AMFT1D_05	ACH	Position 1 (Up)	MERV 8	N	3	64	57	73	127

* a fixed constant

† layover, speed reflects train moving to switch tracks within rail yard

Average total speed = distance traveled / total trip time

Average moving speed = distance traveled / total time in motion



Figure 2.1. Placement of HEPA scavenger unit in passenger car during dynamic tests.

2.1.3 Locomotive static sampling

The sampling plan for the engine locomotives under static conditions is shown in Table 2.3. Due to the design of the locomotives, it was not possible to change any of the ventilation conditions. Therefore, measurements were made under standard operating conditions: standard ACH (15 ACH), damper position as is, HVAC with a MERV8 filter, and no HEPA scavenger.

Table 2.3. Locomotives static sampling plan

Sampling Condition ID	Vent. Rate*	Vent. Damper*	Filter Type	HEPA Scavenger	# Experimental Runs
<i>Locomotive1 - Diesel</i>					
Loco1_01	ACH	Position 1 or 2	MERV8	N	3
<i>Locomotive2 - Electric</i>					
Loco2_01	ACH	Position 1 or 2	MERV8	N	3

* a fixed constant

2.2 Aerosol generation

We developed a protocol for generating aerosols in the 0.3 – 5 μm size range using a Collison Nebulizer (MRE-3jet with attached pressure gauge) with a 70:30 mixture of propylene glycol and vegetable glycerin. The nebulizer in the rail car was connected by an air supply line (3/8"; 200 psi; Continental, ContiTech) to a high-pressure air supply (average psi = 128.34; sd = 3.32) located in the machine shop at the railyard (Figures 2.2a and 2.2c). A HEPA filter was placed in-line to filter the shop air prior to it entering the nebulizer (Figure 2.2b). The nebulizer was placed on a stand 1.0 m above the floor with the outlet 0.2 m

above that for a total of 1.2 m. This height is equivalent to the distance from the floor to the middle part of the seat's headrest, making it a good approximation for the height of a person's breathing zone.

Each experimental run lasted approx. 30 minutes, with the Collision nebulizer generating the aerosol for the first 15 minutes (aerosol concentration increase) and no aerosol generation for the second 15 minutes (aerosol concentration decrease).

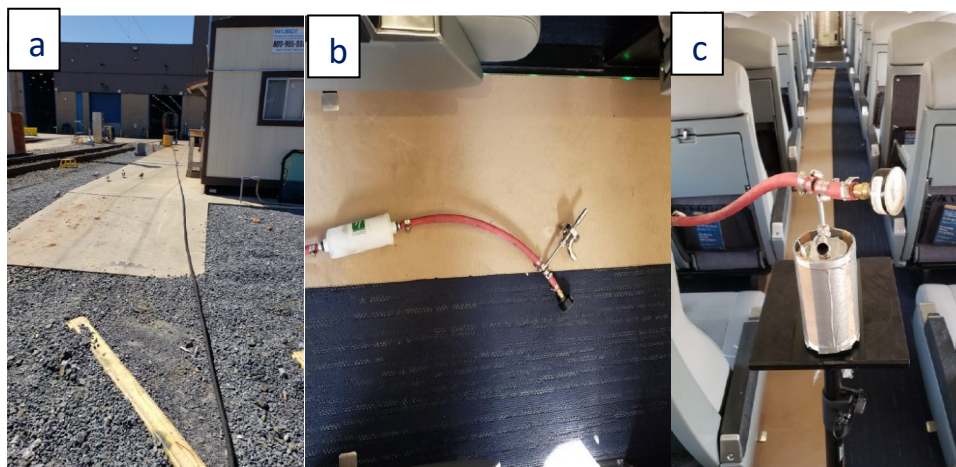


Figure 2.2. Pressured-air delivery system setup. (a) High pressure air line from maintenance shop, (b) in-line HEPA filter to clean supply air, and (c) Collision nebulizer in rail car.

2.3 Direct reading measurements

Real-time aerosol concentrations were measured at multiple locations in the passenger cars and locomotives using photodetector particle counters (AeroTrak Handheld Particle Counter - Model 9306; TSI; Shoreview, MN). The AeroTraks count particles using a laser beam and photodetector to detect light scattering and provides particle counts in 6 size ranges: $<0.3 \mu\text{m}$, $0.3\text{-}0.5 \mu\text{m}$, $0.5\text{-}1.0 \mu\text{m}$, $1\text{-}3 \mu\text{m}$, $3\text{-}5 \mu\text{m}$, and $5\text{-}10 \mu\text{m}$. It also yields particle size distributions by number.

In the passenger cars, four Aerotrak units were placed at different locations within the cars, two on each side of the nebulizer, with one placed on a seat (0.5 m from floor) and one elevated on the luggage rack (1.6 m from floor) so that each end of the car had two AeroTraks at seat level and two at eye level

(Figure 2.3). Aerosol concentration measurements were logged at 1-minute intervals for each experiment and downloaded to a computer as .csv files at the end of each monitoring day.

In the locomotives, one Aerotrak was placed on the engineer’s seat while another one was placed on the assistant engineer seat, both 0.5 m from floor (Figure 2.4). Aerosol concentration measurements were logged at 1-minute intervals for each experiment and downloaded to a computer as .csv files at the end of each monitoring day.

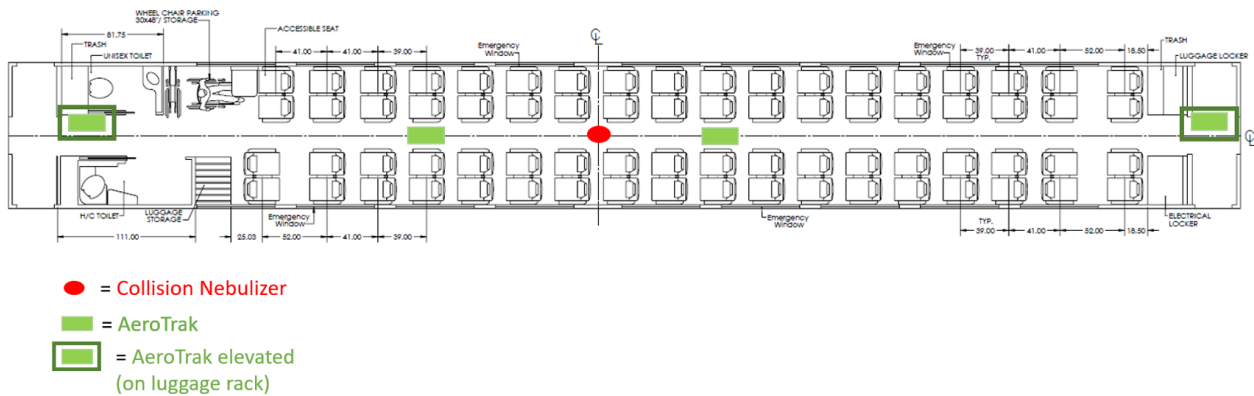


Figure 2.3. Sampling instrument locations in passenger rail car.

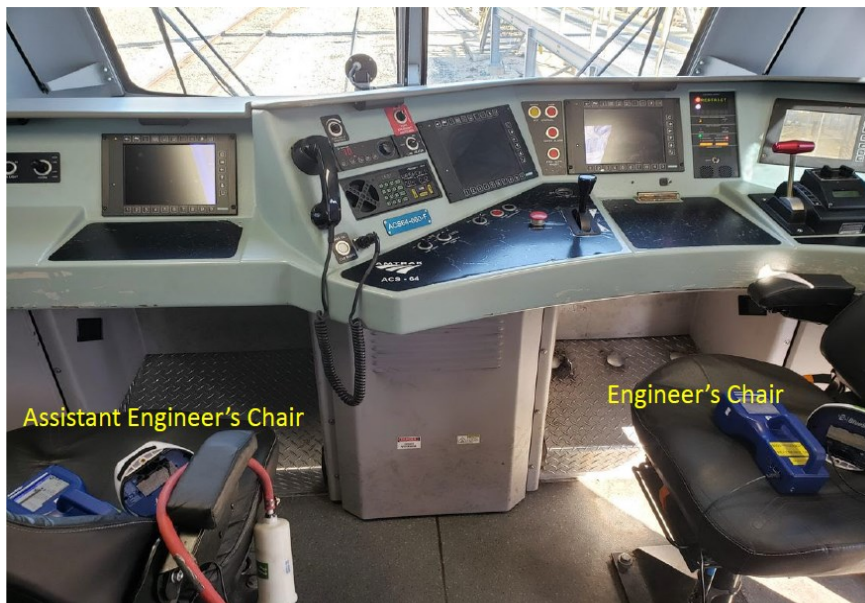


Figure 2.4. Location of measurements in the electric locomotive at the Engineer’s and Assistant Engineer’s seats.

2.4 Data analysis

2.4.1 Calculating average aerosol concentrations

The data collected from the Aerotrak units were logged every minute. These were averaged to obtain an average particle concentration for each particle size range in each of the experimental conditions.

2.4.2 Calculating ACH values

The ventilation system of the cars was designed so that supply air comes in at regularly spaced intervals along the sides of the car and exists through the return-air ducts at both the ends of the car. A well-mixed room (WMR) model can be applied to this situation. The WMR models a room of volume (V ; ft^3) with a constant ventilation airflow rate of (Q ; cfm) where an airborne contaminant is being generated at some rate (G ; $\text{mass or number/min}$) to produce a contaminant concentration inside the room (C_{in} ; $\text{mass or number/ft}^3$). In this case, V was the measured volume of the cars/locomotives, Q was the flow rate of the air entering and leaving the cars/locomotives, G was the rate that aerosol particles were generated (in number/min), and C_{in} was the number of particles in each size range measured in the space (in number/ft^3). This model assumes a balance in the volumetric rate (cfm) of air entering and leaving a room. That is, the Q entering the space is equivalent to the Q leaving the space.

It is also assumed that C_{in} will be reduced by both ventilation and non-ventilation elements (Q and non- Q or k_L). For aerosols, these non-ventilation elements (k_L ; min^{-1}) include gravitational settling, diffusion on to walls, impaction losses, thermophoresis, and condensation/evaporation, the influence of each depending on the size of the aerosol. Furthermore, in the case of viral infectious aerosols, they will also include virus decay. All non-ventilation loss mechanisms are combined into one term k_L and denoted as the loss rate coefficient or the fractional mass of contaminant in the room removed per minute. Thus, ventilation and non-ventilation elements ($Q + k_L$) decrease the amount of contaminant in the room. The resulting mass balance equation is a differential equation with a solution for a contaminant concentration at time (t) given by:

$$C(t) = \frac{G + C_{IN}Q}{Q + k_L V} \left(1 - \exp\left(-\frac{Q + k_L V}{V}t\right)\right) + C(o) \exp\left(-\frac{Q + k_L V}{V}t\right) \quad (\text{Eq. 2.1})$$

Assuming the air within the car is contaminant-free at the beginning of each experiment ($C_o = 0$), the equation reduces to:

$$C(t) = \frac{G + C_{IN}Q}{Q + k_L V} \left(1 - \exp\left(-\frac{Q + k_L V}{V}t\right)\right) \quad (\text{Eq. 2.2})$$

This is referred to as the generation phase and is modeling when a contaminant is being generated and the concentration in the car is increasing. When the contaminant generation ceases ($G = 0$), its concentration starts decreasing over time and Equation 2.1 is reduced to:

$$C(t) = C(o) \exp\left(-\frac{Q + k_L V}{V}t\right) \quad (\text{Eq. 2.3})$$

This is also known as the purging equation, where C_o is now the peak contaminant concentration reached in the car prior to ending G .

Note that the exponential term, $\left(\frac{Q + k_L V}{V}\right)$, is the total removal rate of the contaminant, including both ventilation and non-ventilation elements ($Q + k_L$). As previously stated, k_L depends on particle size, and increases/decreases in proportion to particle size. Therefore, as particle size increases the influences of gravitational settling, impaction, and other non-ventilation mechanisms play greater roles in the particles' dynamics and increase the magnitude of k_L . However, as particle size decreases, many non-ventilation mechanisms play lesser roles in aerosol movement and these smaller particles ($< 0.5 \mu\text{m}$) are more heavily influenced by ventilation and airflow. This allows for the smaller particle removal rate to be used as an estimation for the number of changes per unit time. When the log of $C(t)$ is plotted against time, a straight line is obtained with a slope of $\frac{-Q}{V}$.

This approach was used to estimate ACH values using data from the AeroTraks. Since the data obtained using the AeroTrak units represent the four different locations where the AeroTraks were located, it should show roughly equivalent (within $\pm 5\text{-}10\%$) ACH values throughout the car if it truly is a WMR scenario. Any differences are likely spatial heterogeneity in ventilation. This approach was also used to estimate the removal rate of larger particles ($> 0.5 \mu\text{m}$).

2.4.3 Estimating Risk of Exposure

To estimate the risk of exposure, we used a modeling approach following Miller et al. (2021). Briefly, this approach assumes that all passengers maintain at least 6 ft distance between them. Because large droplets quickly settle out of the air, this social distancing limits the impact of droplets and focuses on risk due to aerosols. The model also makes the following assumptions:

1. There is a 0.3% probability of an infected person being a passenger in the car. This is based on previous experience with the prevalence of infection in the broader community during the pandemic and adopted by Miller et al.¹⁶ (2021);
2. There is no prior infectious material in the car before the trip begins;
3. The latent period of the disease is longer than the length of the model;
4. Infectious aerosols are evenly distributed throughout the cabin volume;
5. Infectious aerosols are removed by a first-order process that includes ventilation (air changes per hour or ACH), deposition, and viral inactivation.

In this model, the probability of exposure is assumed to be related to the number of quanta (airborne virus) inhaled. Quanta are used to represent infectious respiratory aerosol when the actual viral dose in the aerosol and the human dose-response required to cause infection are unknown.^{17,18} The average concentration of quanta in a room (C_{avg}) can be estimated as:

$$C_{avg} = \frac{E}{LV} \left[1 - \frac{1}{LD} (1 - e^{-LD}) \right] \quad (\text{Eq. 2.4})$$

Here, E is the quanta emission rate, L is the sum of all loss processes, D is the duration of the exposure, and V is the volume of the room. The emission of quanta is an uncertain parameter. Buonanno et al. (2020) estimated 50th percentile emissions of 0.36, 4.9, and 31 q/hr for resting, speaking at light activity, and speaking loudly or singing, respectively. We assumed a value of 10 q/hr. For all the modeling presented here, we estimated the deposition of virus containing aerosols to surfaces as 0.3 hr⁻¹, assuming most particles are between 0.3 and 1 µm in a furnished room with low airspeed.¹⁹ Values between 0.2-2.0 hr⁻¹ have been reported in the literature depending on air speed and particle size distribution. The natural decay rate of the virus has been assumed to be 0.32 hr⁻¹. By assuming a breathing rate of 0.8 m³/hour for the passengers in the car, we can estimate the number of quanta inhaled by uninfected people and estimate the probability of exposure. The probability of exposure (P_e) is modeled as:

$$P_e = 1 - \exp(-n) \quad (\text{Eq.2.5})$$

Here, n is the number of inhaled quanta. The quanta required for an infection to occur remains a highly uncertain value for COVID-19. The expected number of cases can be obtained by multiplying the probability of exposure by the number of uninfected people in the space (i.e. railcar).

2.4.4 Statistical Analysis

A three-way or multi-factor analysis of variance (ANOVA) was used to determine if any of three exposure-control measures significantly influenced the average aerosol concentrations in the cars (null hypothesis (H_0): all group means are equal). An ANOVA will only indicate if there is or is not a statistically significant difference in the average aerosol concentrations between experimental conditions and will not identify which conditions are different. In other words, it will indicate if any of three exposure-control measures influenced the average aerosol concentrations, but it will not identify which exposure-control measure(s) is/was responsible. Therefore, to assess the impact each control measure had on the aerosol removal rate/ACH, we used multiple linear regression with a subsequent F-test to identify the statistical significance of the differences seen between exposure control measure use across aerosol size groups.

3. RESULTS

3.1 Size distribution generated by Collison nebulizer

Particle sizes generated by the Collison nebulizer were lognormally distributed as shown in Figure 8 with a geometric mean diameter of 0.19 μm and a geometric standard deviation of 1.55 μm .

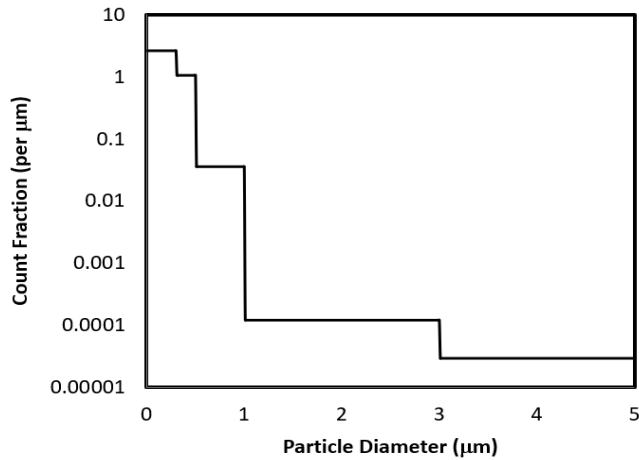


Figure 3.1. Distribution of count fraction per micrometer by particle diameter.

3.2 Passenger railcars

3.2.1 Effect of study variables on particle air concentrations – STATIC Conditions

The results of the comparison of aerosol concentrations by size across the different sampling scenarios are shown in Table 3.1. For all sizes except those aerosols greater than or equal to 5 μm in diameter, the average concentrations differ across the sampling scenarios. Figure 3.2 shows the effects of damper position, filter type, and the presence/absence of a HEPA scavenger on average concentrations of smaller particles ($\leq 1.0 \mu\text{m}$) and larger particles ($> 1.0 \mu\text{m}$), respectively, in the passenger car. Together, these show that regardless of particle size, the damper position does not have a statistically significant effect on the average concentrations of particles in the rail car. These results also indicate that the higher efficiency MERV13 filters reduce the average air concentrations of particles, particularly for particles $< 0.3 \mu\text{m}$. There is no significant effect for larger particles, likely because of the smaller number of larger particles in the aerosol. Furthermore, these results also suggest that the HEPA scavenger does not have a significant effect on air concentrations of particles in any size range.

Table 3.1. ANOVA - Aerosol concentrations by sampling scenario under static conditions

		Sum of Squares	df	Mean Square	F	Sig.
0.3 µm Concentration	Between Conditions	2.76 x 10 ¹²	7	3.95 x 10 ¹¹	7.69	6.72 x 10 ⁻⁵ ***
	Within Conditions	1.23 x 10 ¹²	24	5.13 x 10 ¹⁰		
	Total	4.00 x 10 ¹²	31			
0.5 µm Concentration	Between Conditions	4.18 x 10 ¹¹	7	6.00 x 10 ¹⁰	6.40	0.0003***
	Within Conditions	2.24 x 10 ¹¹	24	9.30 x 10 ⁹		
	Total	6.42 x 10 ¹¹	31			
1.0 µm Concentration	Between Conditions	3.15 x 10 ¹⁰	7	4.50 x 10 ⁹	3.79	0.007***
	Within Conditions	2.85 x 10 ¹⁰	24	1.19 x 10 ⁹		
	Total	6.00 x 10 ¹⁰	31			
3.0 µm Concentration	Between Conditions	4.12 x 10 ⁷	7	5.89 x 10 ⁶	3.12	0.02**
	Within Conditions	4.53 x 10 ⁷	24	1.89 x 10 ⁶		
	Total	8.65 x 10 ⁷	31			
5.0 µm Concentration	Between Conditions	7.53 x 10 ⁵	7	1.08 x 10 ⁵	1.06	0.42
	Within Conditions	2.34 x 10 ⁶	24	1.01 x 10 ⁵		
	Total	3.19 x 10 ⁶	31			

*** p<0.01, ** p<0.05, * p<0.1

Note: Conditions refers to the eight different sampling conditions used to evaluate the exposure controls (see Table 2.1).

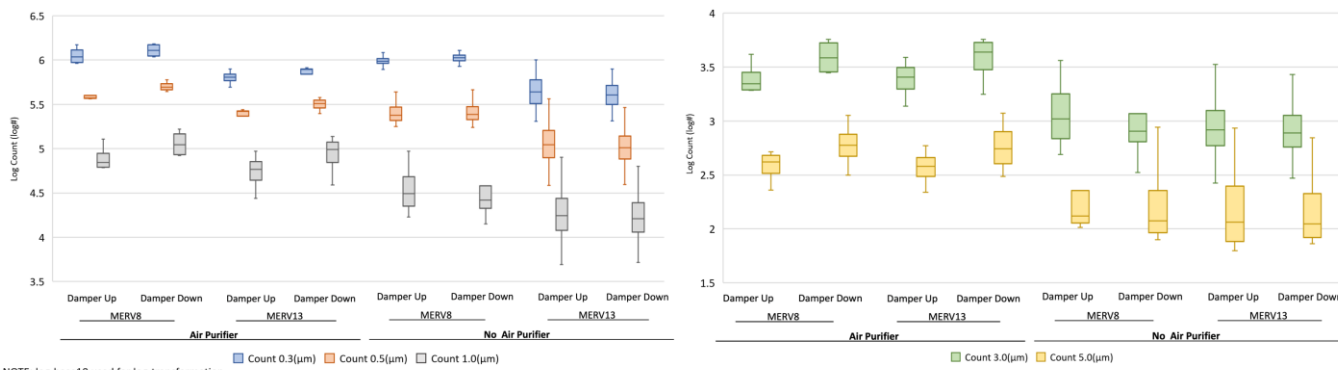


Figure 3.2. Comparison of aerosol concentrations of particles across different experimental conditions during static testing in passenger railcars. Smaller particles (<0.3 µm, 0.3-0.5 µm, and 0.5-1.0 µm) shown left and larger particles (1-3 µm, 3-5 µm) shown right.

3.2.2 Effect of study variables on particle removal rates – STATIC Conditions

A multiple linear regression was run to understand how much the aerosol removal rate will change when the exposure control variables change under static conditions (Table 3.2). The filter type had a statistically significant effect on the aerosol removal rate for all particle sizes ($p < 0.01$; $R^2 = 0.24$ to 0.56). The location of sample collection in the car also indicated statistically significant effects on the aerosol removal rates across all particle sizes ($p < 0.015$). However, the subsequent F-test indicated that only the interaction between the particle removal rate and filter type indicated statistically significant differences

in removal rates across the different particle sizes when using different filter types ($p < 0.01$) (Figure 3.3). There were no statistically significant differences between particle removal rate across particle size and sample location ($p = 0.35$).

Table 3.2. Coefficients for ACH by aerosol size under static conditions

VARIABLES	AEROSOL SIZE				
	5.0 μm	3.0 μm	1.0 μm	0.5 μm	0.3 μm
Damper position	2.15** (1.06)	1.35 (0.90)	0.18 (0.54)	0.58 (0.58)	0.37 (0.38)
Filter type	-3.60*** (1.24)	-6.00*** (1.05)	-7.54*** (0.64)	-8.37*** (0.68)	-6.43*** (0.44)
HEPA air purifier	-0.92 (1.06)	-1.25 (0.90)	-0.42 (0.54)	0.35 (0.58)	0.04 (0.38)
Sampler location					
B side	5.35*** (1.51)	4.27*** (1.28)	2.03* (0.78)	0.40 (0.83)	0.95* (0.54)
Row 12	9.75*** (1.51)	9.59*** (1.28)	6.48*** (0.78)	2.91*** (0.83)	2.54*** (0.54)
Row 5	2.60* (1.51)	2.09 (1.28)	1.38* (0.78)	0.27 (0.83)	0.69 (0.54)
Constant	10.46*** (1.62)	13.72*** (1.37)	16.58*** (0.83)	16.11*** (0.89)	12.41*** (0.58)
Observations	192	192	192	192	192
R-squared	0.24	0.35	0.55	0.48	0.56

Standard errors in parentheses
 *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

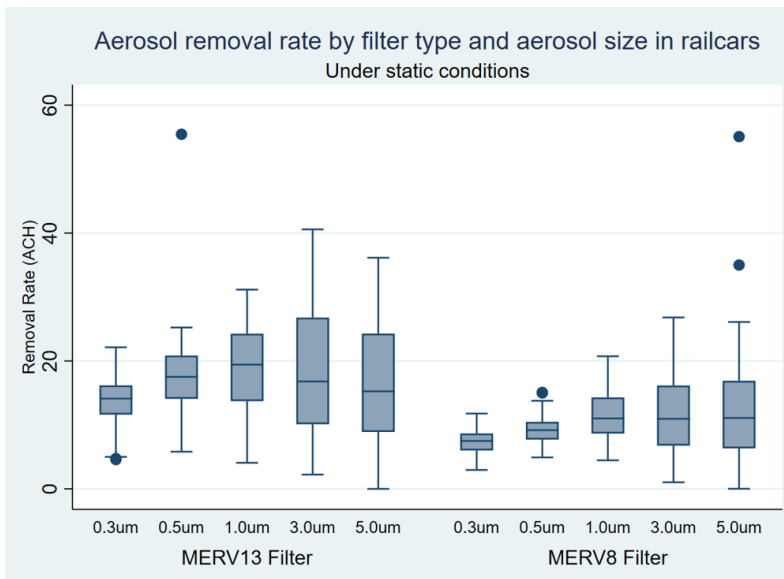


Figure 3.3. Aerosol removal rates across all particle sizes using MERV13 and MERV8 filters.

3.2.3 Effect of study variables on particle air concentrations – DYNAMIC Conditions

Given the constraints of a moving train, the damper position nor the filter type could be changed. However, we were able to install the HEPA scavenger unit (Figure 2.1) and operate it at high and low fan speeds. The train traveled approximately 300 miles, averaging 75.6 mph with a max speed of 127 mph (Table 2.2).

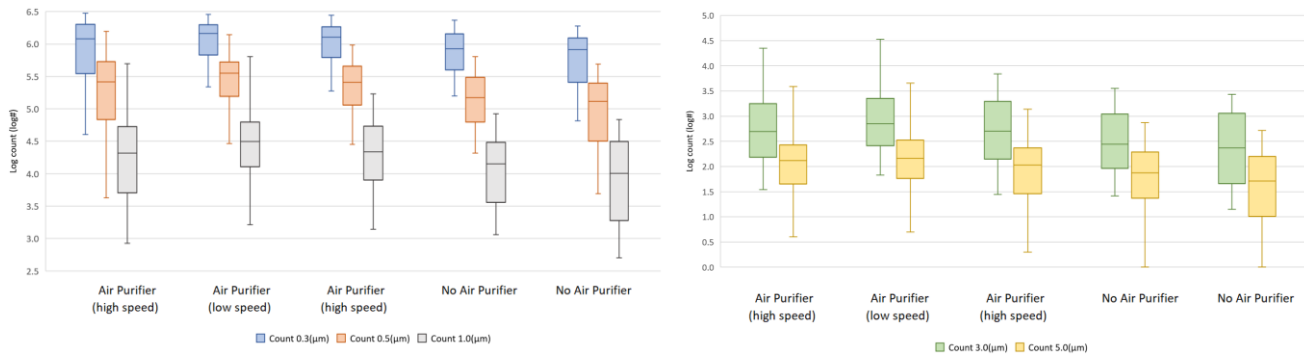
The results of the comparison of aerosol concentrations by size across the different sampling scenarios are shown in Table 3.3. For all sizes except those aerosols less than or equal to 0.3 μm in diameter, the average concentrations of aerosols did not differ across the sampling scenarios. Figure 3.4 shows the effects of the presence/absence of a HEPA scavenger at varying fan speeds on the average concentrations of smaller particles ($\leq 1.0 \mu\text{m}$) and larger particles ($> 1.0 \mu\text{m}$), respectively, in the passenger car. Regardless of particle size, the presence/absence of the HEPA scavenger does not have a statistically significant effect on the average concentrations of particles in the rail car.

Table 3.3. ANOVA - Aerosol concentrations by sampling scenario under dynamic conditions

		Sum of Squares	df	Mean Square	F	Sig.
0.3 μm Concentration	Between Conditions	1.1×10^{12}	4	2.6×10^{11}	2.50	0.09*
	Within Conditions	1.6×10^{12}	15	1.1×10^{11}		
	Total	2.6×10^{12}	19			
0.5 μm Concentration	Between Conditions	2.3×10^{11}	4	5.7×10^{10}	2.26	0.11
	Within Conditions	3.8×10^{11}	15	2.5×10^{10}		
	Total	6.0×10^{11}	19			
1.0 μm Concentration	Between Conditions	8.7×10^9	4	2.2×10^9	1.41	0.28
	Within Conditions	2.3×10^{10}	15	1.5×10^9		
	Total	3.2×10^{10}	19			
3.0 μm Concentration	Between Conditions	1.3×10^7	4	3.33×10^6	1.01	0.44
	Within Conditions	5.00×10^7	15	3.32×10^6		
	Total	6.30×10^7	19			
5.0 μm Concentration	Between Conditions	4.71×10^5	4	1.18×10^5	0.80	0.54
	Within Conditions	2.21×10^6	15	1.47×10^5		
	Total	2.68×10^6	19			

*** p<0.01, ** p<0.05, * p<0.1

Note: Conditions refers to the five different sampling conditions used to evaluate the exposure controls (see Table 2.2).



NOTE: log-base10 used for log-transformation

Figure 3.4. Comparison of aerosol concentrations across different experimental conditions during dynamic testing in passenger railcars. Smaller particles (<0.3 μm, 0.3-0.5 μm, and 0.5-1.0 μm) shown left and larger particles (1-3 μm, 3-5 μm) shown right.

3.2.4 Effect of study variables on particle removal rates – DYNAMIC Conditions

A multiple regression model was run to understand how much the aerosol removal rate will change when the exposure control variables change under dynamic conditions (Table 3.4). Use of the HEPA air purifier at both high and low fan speeds showed a statistically significant difference in the removal rate of aerosols $\leq 1.0 \mu\text{m}$ when compared to not using the air purifier ($p < 0.05$; $R^2 = 0.34$ to 0.54). We could not assess impact of changing the damper position or filter efficiency as these two things were unable to be change while the train was in motion. The location of sample collection in the car also indicated statistically significant effects on the aerosol removal rates across all particle sizes ($p < 0.05$). However, the subsequent F-tests on

Table 3.4. Coefficients for ACH by aerosol size under dynamic conditions

VARIABLES	AEROSOL SIZE				
	5.0 μm	3.0 μm	1.0 μm	0.5 μm	0.3 μm
Damper position	-	-	-	-	-
Filter type	-	-	-	-	-
HEPA air purifier					
High speed	3.57 (2.94)	1.01 (2.39)	-0.63*** (1.13)	-1.22** (0.58)	-0.80* (0.40)
Low speed	0.35 (3.33)	-0.43 (2.70)	-2.67** (1.18)	-2.63*** (0.66)	-1.69*** (0.45)
Sampler location					
B side	-11.43*** (3.14)	-6.87 2.55	-2.11* (1.20)	-1.02 (0.62)	-0.69 (0.42)
R12	-9.97*** (3.13)	-5.98** (2.55)	-0.84 (1.20)	-0.12 (0.61)	0.80* (0.42)
R5	-1.11 (3.06)	1.86 (2.48)	2.17* (1.17)	1.63 (0.60)	1.47*** (0.41)
Constant	21.13*** (3.16)	19.07*** (2.57)	13.72*** (1.21)	11.42*** (0.63)	8.99*** (0.42)
Observations	42	42	42	42	42
R-squared	0.40	0.33	0.34	0.49	0.54

Damper position and filter type remained constant

Standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

the interaction between particle removal rate across particle size and use of the air purifier and sample location indicated that there were no statistically significant differences across groups ($p = 0.87$ and 0.86 , respectively).

3.3 Locomotives

3.3.1 Effect of study variables on particle air concentrations- STATIC Conditions

Results comparing the average concentrations of particles in different size ranges in both the diesel-powered and electric-powered locomotives are shown in Figure 3.3. The differences in the particle concentrations for the Engineer and the Assistant Engineer locations do not appear different for the two types of locomotives. However, there is a difference in the amount of total aerosol volume generated in each locomotive.

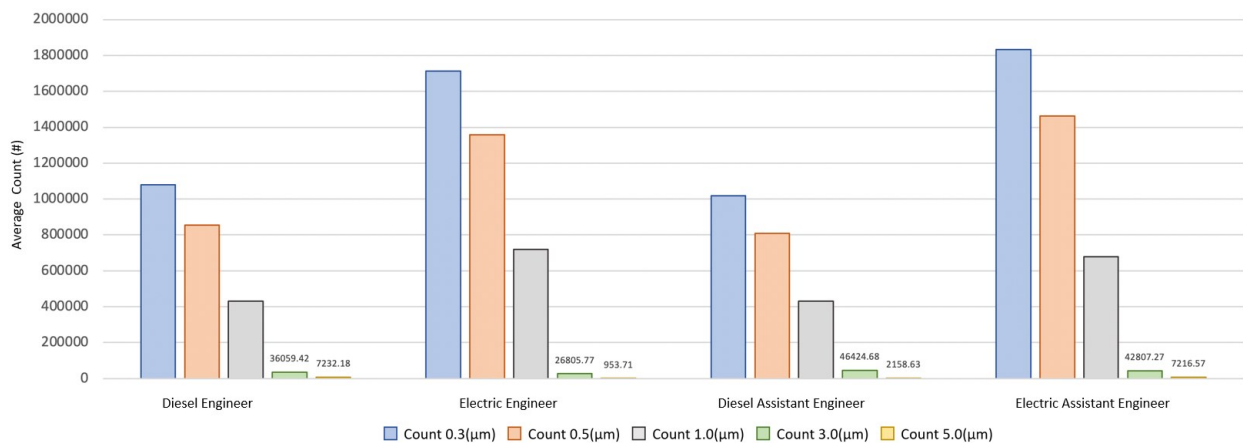


Figure 3.5. Comparison of aerosol concentrations of particles in different size ranges in the diesel-powered and electric-powered locomotives.

3.3.2 Effect of study variables on particle removal rates – STATIC Conditions

Results comparing the average removal rate of particles in different size ranges in both the diesel-powered and electric-powered locomotives are shown in Figure 3.6. The differences in the particle removal rates both locomotives and for the Engineer and the Assistant Engineer locations within each locomotive do not appear different. Using the removal rates for particles $<0.5 \mu\text{m}$, the air changes values of the HVAC

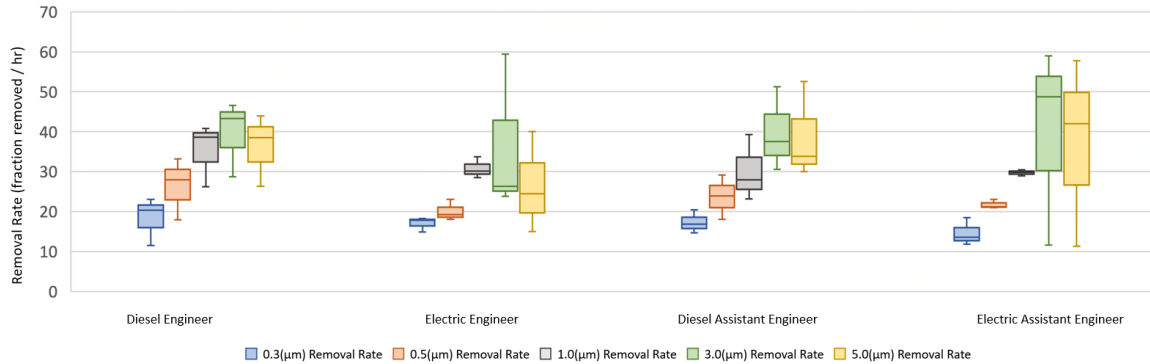


Figure 3.6. Comparison of aerosol removal rates of particles in different size ranges in the diesel-powered and electric-powered locomotives.

system with MERV8 filters in place were calculated to be between 17-35 ACH. ANOVA and regression analysis were not run for these scenarios as assessment of the standard operating conditions were the focus of this part of the study and no conditions were changed.

3.4 Risk of exposure in passenger railcars and locomotives

We used a modeling approach following Miller et al. (2021) to estimate the probability of exposure in the passenger car. As previously mentioned (Methods Section C4.3), this approach assumes that 0.3%

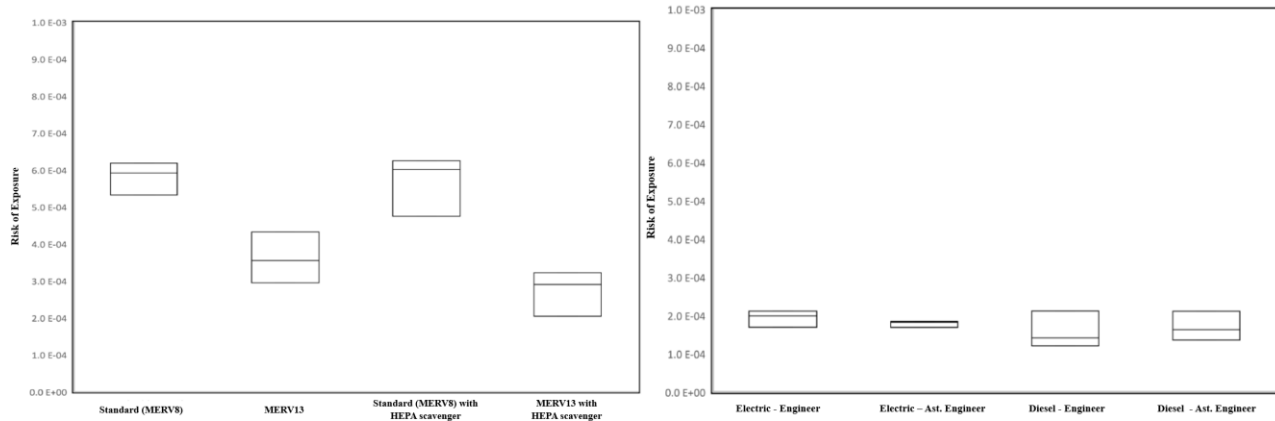


Figure 3.7. Risk of exposure distribution in a passenger railcar (left) and in engine locomotives (right).

of the passenger population is infected in the car and that all passengers maintain at least 6 ft distance between them.

Figure 3.7 shows the risk of exposure distribution in a passenger railcars and engine locomotives. In the railcar, the risk (probability) of exposure under standard conditions is 0.06%. The risk is unchanged with the introduction of a HEPA air scavenger. However, the risk of exposure was reduced by 42% using a MERV13 filter, and further reduced by 50% with both a MERV13 filter and the HEPA scavenger in use. For the engine locomotives, there are no significant differences in risk between the Engineer and Assistant Engineer locations in either locomotive type and no differences between the two types of locomotives.

4. DISCUSSION

The results of this study suggest that increasing the efficiency of the HVAC filters in the railcar (i.e. changing to a higher MERV rating) reduced the overall average concentration of respirable-sized particles, increased the removal rate of those particles from the space, and reduced the risk of exposure should those particles contain COVID-like or other infectious agents of a similar size.

Similar to the results of previous studies investigating COVID transmission on public transit,²⁰⁻²³ our findings are consistent with previous studies that showed low risk of exposure to SARS-CoV-2 from use of mass transit systems when the route of exposure is via aerosols. Furthermore, our results show that the most effective way to reduce the risk of exposure for passengers and for industry employees is also the more efficient – a simple upgrading of the HVAC filter.

While other studies on COVID and related infectious-disease transmission in public transit^{6,24,25} suggested that these systems may play a large role in community spread of viruses, most of these were conducted before or at beginning of pandemic when masking and social distancing not enforced. These prior studies also did not consider the influence of exposure control elements on the risk of exposure and were left to assess how transmission might occur under standard, pre-COVID, procedures.

To the author's knowledge, this work is the first to incorporate a risk of exposure analysis along with an exposure assessment to assess the effectiveness of various exposure control measures on public transit, let alone on public transit used primarily for long-distance commuting where passengers are likely to spend greater amounts of time. Furthermore, this study also developed and validated its own protocol for generating respirable-sized aerosols for use in this work rather than reliance on theoretical models to predict particle concentrations. Finally, by conducting an assessment of the engine locomotives, we included an occupational risk assessment independent of the risk assessment for passengers.

Although this work is a key step in assessing the effectiveness of various exposure control methods to respirable infectious agents, it is limited in that many of the controls (particularly the filters) could not be evaluated during dynamic testing. Furthermore, no measurements were taken with passengers, limiting the evaluation of human behavior on aerosol transport. However, as the same railcar was used in both the static and dynamic tests, and as similar HVAC systems are used in both the railcars and the types of locomotives evaluated, it is reasonable to consider that similar results would be seen when the railcar is in motion and in the engine locomotives. Additionally, since the results indicate that the cars were not well-mixed and had differences in particle concentration and removal rates, these conditions might be a reasonable representation of when passengers are present and moving about. Finally, the risk calculation relied on estimating the quanta emission rate rather than using the infectious dose as the dose-response relationship for SARS-CoV-2 is still uncertain.

The results presented here show that a simple upgrade of the efficiency of the HVAC filters in public transit vehicles results in a clear reduction in particle concentration and reduction in the risk of exposure. Replacing the existing MERV8 filters with a new one does not lower particle concentration or exposure risk. Widespread upgrading of HVAC filter efficiency in public transit vehicles could help reduce the extent of community-spread infectious respiratory diseases, protect workers essential to the functioning of our cities, and overall contribute to slowing of current and future disease spread.

REFERENCES

- 1 MTA(NYC). *Subway and bus ridership for 2020*, <<https://new.mta.info/agency/new-york-city-transit/subway-bus-ridership-2020>> (2020).
- 2 Chia, P. Y. *et al.* Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. *Nature Communications* **11**, doi:10.1038/s41467-020-16670-2 (2020).
- 3 Liu, Y. *et al.* Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. *Nature* **582**, 557-560, doi:10.1038/s41586-020-2271-3 (2020).
- 4 Tang, S. *et al.* Aerosol transmission of SARS-CoV-2? Evidence, prevention and control. *Environment International* **144**, 106039, doi:10.1016/j.envint.2020.106039 (2020).
- 5 Harris, J. E. The Subways Seeded the Massive Coronavirus Epidemic in New York City. *SSRN Electronic Journal*, doi:10.2139/ssrn.3574455 (2020).
- 6 Zhao, S. *et al.* The association between domestic train transportation and novel coronavirus (2019-nCoV) outbreak in China from 2019 to 2020: A data-driven correlational report. *Travel Medicine and Infectious Disease* **33**, 101568, doi:10.1016/j.tmaid.2020.101568 (2020).
- 7 APTA. *The COVID-19 Pandemic Public Transportation Responds: Safeguarding Riders and Employees.* (2020).
- 8 FTA. *Frequently Asked Questions from FTA Grantees Regarding Coronavirus Disease 2019 (COVID-19)*, <<https://www.transit.dot.gov/frequently-asked-questions-fta-grantees-regarding-coronavirus-disease-2019-covid-19>> (2020).
- 9 MTA(MD). *COVID-19 and MDOT MTA*, <<https://www.mta.maryland.gov/coronavirus>> (2021).
- 10 USDOT. *Coronavirus Resources at the Department of Transportation*, <<https://www.transportation.gov/coronavirus>> (2020).
- 11 WMATA. *Metro and Covid-19: Steps we've taken*, <<https://www.wmata.com/service/covid19/COVID-19.cfm>> (2020).
- 12 ACGIH. *Industrial Ventilation A Manual of Recommended Practice for Design.* 29th Edition edn, (American Conference of Governmental Industrial Hygienists (ACGIH), 2016).
- 13 Hinds, W. C. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles.* 2nd Edition edn, (Wiley-Interscience, 1999).
- 14 Belosi, F., Conte, M., Gianelle, V., Santachiara, G. & Contini, D. On the concentration of SARS-CoV-2 in outdoor air and the interaction with pre-existing atmospheric particles. *Environmental Research* **193**, 110603, doi:10.1016/j.envres.2020.110603 (2021).
- 15 Hu, J. L., C.; Chen, Z.; Liu, W.; Hu, X.; Pei, R.; Su, Z.; Deng, F.; Huang, Y.; Sun, X.; Cao, J.; Guan, W. Airborne SARS-CoV-2 and the Use of Masks for Protection against Its Spread in Wuhan, China. *Preprints*, doi:2020050464 (2020).
- 16 Miller, S. L. *et al.* Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. *Indoor Air* **31**, 314-323, doi:10.1111/ina.12751 (2021).
- 17 Nishiura, H. *et al.* Closed environments facilitate secondary transmission of coronavirus disease 2019 (COVID-19). *medRxiv*, doi:10.1101/2020.02.28.20029272 (2020).
- 18 Watanabe, T., Bartrand, T. A., Weir, M. H., Omura, T. & Haas, C. N. Development of a Dose-Response Model for SARS Coronavirus. *Risk Analysis* **30**, 1129-1138, doi:10.1111/j.1539-6924.2010.01427.x (2010).
- 19 Buonanno, G., Stabile, L. & Morawska, L. Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. *Environment International* **141**, 105794, doi:10.1016/j.envint.2020.105794 (2020).
- 20 SPF. *COVID-19 : point épidémiologique du 4 juin 2020*, <<https://www.santepubliquefrance.fr/maladies-et-traumatismes/maladies-et-infections-respiratoires/infection-a-coronavirus/documents/bulletin-national/covid-19-point-epidemiologique-du-4-juin-2020>> (2020).

- 21 Hu, M. *et al.* Risk of Coronavirus Disease 2019 Transmission in Train Passengers: an Epidemiological and Modeling Study. *Clinical Infectious Diseases* **72**, 604-610, doi:10.1093/cid/ciaa1057 (2021).
- 22 Moreno, T. *et al.* Tracing surface and airborne SARS-CoV-2 RNA inside public buses and subway trains. *Environment International* **147**, 106326, doi:10.1016/j.envint.2020.106326 (2021).
- 23 Silcott, D., Kinahan, S., Santarpia, J., Silcott, B., Silcott, R., Silcott, P., Silcott, B., Distelhorst, S., Herrera, V., Rivera, D., Crown, K., Lucero, D., Bryden, W., McLoughlin, M., Cetta, M., Accardi, R. TRANSCOM/AMC Commercial Aircraft Cabin Aerosol Dispersion Tests. (2020).
- 24 Goscé, L. & Johansson, A. Analysing the link between public transport use and airborne transmission: mobility and contagion in the London underground. *Environmental Health* **17**, doi:10.1186/s12940-018-0427-5 (2018).
- 25 Zhen, J., Chan, C., Schoonees, A., Apatu, E., Thabane, L., Young, T. Transmission of respiratory viruses when using public ground transport : a rapid review to inform public health recommendations during the COVID-19 pandemic | South African Medical Journal. *South African Medical Journal* **110**, doi:doi.org/10.7196/SAMJ.2020.v110i6.14751 (2020).

CURRICULUM VITAE

Kelsey R. Babik, MPH
121 S Fremont Ave. Apt 329
Baltimore, MD 21201
814-691-1973
kbabik2@jhu.edu
kelsey.babik@gmail.com

Education

Johns Hopkins Bloomberg School of Public Health (BSPH) Summer 2021
ScM Exposure Sciences and Environmental Epidemiology Baltimore, MD
Certificate in Risk Sciences and Public Policy

University of Maryland Graduated May 2015
MPH Environmental Health Sciences College Park, MD

University of Pittsburgh Graduated April 2012
BS Molecular Biology, Chemistry and US History minors Pittsburgh, PA

Experience

COVID-19 Case Investigator/Contact Tracer August 2020 to present
Baltimore City Health Department (BCHD) and BSPH
Baltimore, MD

PIs: Darcy Phelan-Emrick (Darcy.Phelan@baltimorecity.gov) and Emily Gurley (egurley1@jhu.edu)

This practice-ship aims to provide students with on-the-job training in applied epidemiology and to support COVID-19 pandemic response efforts at BCHD. Overall, I was responsible for assisting BCHD with COVID-19 contact tracing efforts, including training, and monitoring the speed and performance of contact tracing operations.

- **Maintaining contact tracing materials and updating with new protocols and processes**
- **Managing contact tracing trainings**
- **Support volunteers making calls to confirmed COVID-19 cases and their close contacts**
- **Conduct quality assurance of work and systems**
- **Create daily reports that include key performance indicators and suggestions for improvements to digital content management systems**
- **Serve as the point of contact for collaborative contact tracing related efforts between the BCHD and BSPH**

Occupational Risk Asmt. Research Assistant June 2019 to December 2019
BSPH Baltimore, MD

PI: Mary Fox (mfox9@jhu.edu)

This project involved an occupational epidemiology analysis and an occupational health risk assessment for the Virginia Joint Legislative Audit and Review Commission's (JLARC) review of Virginia's Workers' Compensation Disease Presumptions for first responders ([§ 65.2-402](#) and [§ 65.2-404](#)). Specific tasks included:

- Identification and assessment of existing research on occupation-disease associations;
- Summary of findings from methodologically sound and independent studies;

- Assessment of Virginia’s requirements to claim cancer presumption.

As a direct result of this work:

- JLARC produced and presented a report to the VA legislature, “[Virginia’s Workers’ Compensation System and Disease Presumptions](#)”
- The VA legislature passed into law [Senate Bill 9 \(2020\)](#) and [HB 438 \(2020\)](#) expanding the health conditions that are compensable under law and making it easier for first responders to access workers’ compensation benefits.

**MSc Student, Research Assistant
BSPH**

**August 2018 to present
Baltimore, MD**

PI: Gurumurthy “Ram” Ramachandran (gramach5@jhu.edu)

My work is focused on developing predictive mathematical exposure models for exposure to aerosols. Specifically, I am interested in developing models for occupational exposure to aerosols in the respirable and nano-size range, particularly those found in pharmaceutical manufacturing. The models I will develop will be the first of their kind and will be applicable to numerous industries that utilize aerosols beyond the pharmaceutical industry.

**Environmental Health and Safety Engineer
United Therapeutics Corporation**

**March 2017 to July 2018
Silver Spring, MD**

Supervisor: Katherine Wellman (301) 608-9292

- Technically proficient in environmental compliance including wastewater, hazardous waste, hazardous materials management, and chemical reporting.
- Supports program implementation corporate-wide and drives continuous improvement and sustainability practices.
- Technically proficient for health and safety compliance including worker injury and illness prevention; hazardous materials handling; hazardous energy control; occupational exposure limits; biosafety; radiation safety; laboratory safety; PPE assessments; fall protection; and emergency preparedness and response.
- Supports project with knowledge of EHS principles, practice, and regulatory requirements.
- Administers pharmaceutical potent compound safety program including managing the industrial hygiene monitoring, respiratory protection program, and occupational health program.
- Supports business growth by assessing new projects and processes for EHS impact.
- Administers the UT Silver Spring site wastewater discharge control program including agency notifications, monitoring requirements, periodic sampling, user reports, and records retention.
- Administers the UT Research Triangle Park (RTP), NC site wastewater discharge control program including agency notifications, monitoring requirements, periodic sampling, user reports, and records retention during RTP EHS staff shortage.
- Administers the UT Silver Spring site hazardous waste management including chemical and biological waste removal, waste profiles, maintains manifests, conduct inspections, and environmental reporting and records retention.
- Completes chemical reporting and community right-to-know submittals. Maintains inventor records and SDSs of hazardous chemicals and identifies materials on EPA or OSHA lists.
- Administers engineering and work practice controls for hazards such as hazardous energy, flammable liquids, and fall protection.

- Conducts program audits and inspections; makes recommendations through written technical reports; effectively communicates findings; and closes out audit reports.
- Develops, plans, and implements EHS training and awareness programs.
- Maintains EHS records including EHS training records, occupational health records, and occupational incidents/injury reports and records.
- Conducts hazard evaluations of jobs and processes and performs routine inspections of facilities.
- Conducts occupationally-related worker incident/injury investigations with effective root-cause analysis, identifies corrective actions, and tracks to completion.
- Ensures emergency planning and drills are up to date.
- Plans response for emergency situations such as injuries, illnesses, and chemical spills during business and non-business hours.
- Supports other departments and supportive duties as assigned.

Industrial Hygiene Fellow

August 2015 to March 2017

National Institute for Occupational Safety and Health (NIOSH)

Cincinnati, OH

Supervisor: CAPT. Cherie F. Estill (513) 237-8442

- Design and conduct industrial hygiene field evaluations for companies manufacturing and using various nanomaterials.
- Conduct exposure monitoring of various industrial workplaces manufacturing and using nanomaterials and other potentially harmful substances.
- Assist fellow department staff in exposure monitoring of various industries including the firefighting and spray foam installation industries.
- Evaluate work practices, workplace control measures, and relevant health and safety program elements of industries of interest.
- Assist in the recruitment of companies and workers for a cohort study focusing on the long-term effects of exposure to carbon nanotubes.
- Analyze occupational health data and industrial hygiene results to prepare final reports for the employer and agency.
- Develop recommendations for addressing problems or hazards identified during field studies.
- Work with senior staff to prepare talks or posters for conferences or presentations with relevant worker or industry groups.
- Member of National Occupational Research Agenda (NORA) Manufacturing Sector Council and NORA Hearing Loss and Respiratory Health Cross-Sector Council
- Specific Projects:
 - Characterizing workforces exposed to current and emerging nanomaterials in the U.S.
 - Epidemiology study of US carbon nanotube & nanofiber workers
 - Standardizing industrial hygiene data collection forms used by workers' compensation insurers

Research Administration Graduate Assistant

August 2014 to May 2015

University of Maryland School of Public Health

College Park, MD

Supervisor: Dushanka V. Kleinman (301) 405-7201

- Enter and update new and existing research grant proposals in the School of Public Health's Access database by navigating the university-wide Coeus database system.
- Assist the Associate Dean and other faculty members in compiling and organizing all research activity for the Council on Education for Public Health (CEPH) accreditation.

Occupational Health Intern**June 2014 to August 2014****Occupational Safety and Health Administration (OSHA)****Washington, DC**

Supervisors: Drs. Kathleen Fagan and Michael Hodgson (202) 693-2486

- Independently sort through and organize 200 plus cases and records on occupational exposures to isocyanates – a leading cause of work-induced asthma.
- Compile exposure data from isocyanate cases into one central data sheet using two of the databases employed by OSHA.
- Analyze exposure and inspection data to develop inspection and enforcement strategy for OSHA and prevention strategies for employers and present findings to agency.
- Assist fellow resident interns on their projects including the development of a technical document on work-place asthma and a proposal for an occupational surveillance system for salmonella and campylobacter outbreaks in animal-processing workers.

Graduate Research Assistant**January 2014 to May 2015****University of Maryland School of Public Health****College Park, MD**

PI: Amy Sapkota (301) 405-1772

- Perform DNA extractions and PCRs on over 100 samples per week for two different studies, one focusing on the microbiome of tobacco products and the other focusing on the microbiome of wastewater.
- Assist in the development of lab protocols and SOPs for a study focusing on the microbiome of wastewater.
- Responsible for trouble-shooting and fixing faulty equipment as well as installing new instruments.
- Mentor and teach undergraduates working in the lab to give them an enjoyable and rewarding public health lab experience.

SAT Preparatory Instructor**August 2012 to May 2014****Kaplan Test Prep****Washington, DC and Montgomery Co, MD**

Supervisor: Jason Robbins (410) 779-3083

- Guide students through a rigorous program to achieve competitive SAT scores both in a classroom setting and through an online portal.
- Employ various classroom management strategies to allow students to realize their potential as intelligent young adults.
- Motivate high school students to succeed beyond the SAT and college.
- Advise parents and students on the best study package that will help an individual student.
- Participate in numerous marketing events to promote the company.

Technical Writer**May 2013 to August 2013****American Type Culture Collection (ATCC)****Manassas, VA**

Supervisor: Emily Jackson-Machelski (703) 365-2752

- Write and produce documents such as quality control data, work instructions, protocols, forms, Product Information Sheets, Certificates of Analysis and other documents to support manufacturing efforts using SharePoint and Qualtrax software and Microsoft Office.
- Responsible for developing and reviewing content for ATCC website, which requires extensive knowledge of Sitecore software and HTML coding.
- Assist senior writers on their various projects.

**Lab Assistant
NORAC Laboratory**

Director: Ronald Babik (814) 536-8506

**March 2006 to August 2012
Johnstown, PA**

- Independently collected and analyzed public drinking water samples using membrane filtration, heterotrophic plate count, and positive-absence methods.
- Trained in lead-based paint testing and abatement standards used by HUD to rehabilitate impoverished housing as well as mold remediation standards established by the Pennsylvania Department of Environmental Protection (PA DEP).
- Produced written analysis reports for various clients.
- Reported public drinking water sample results to the PA DEP through their electronic lab reporting system (DWELR).
- Assisted in the writing of laboratory SOPs with Microsoft Office software.
- Counseled clients on the various testing services offered and recommended which to use based on the client's situation.

Teaching Assistant Experience BSPH

Methods in Quantitative Risk Assessment

3 credit graduate course, ***online due to COVID-19*** 3rd Term
AY 20-21

Seafood and Public Health: Global Trade, Nutrition, and the Environment

3 credit graduate course, ***online due to COVID-19*** 3rd Term
AY 20-21

Risk Policy, Management, and Communication

AY 20-21 4th Term

3 credit graduate course, ***online due to COVID-19*** 2nd Term

AY 20-21

AY 19-20 4th Term

Topics in Risk Assessment

AY 19-20 4th Term

2 credit graduate seminar course, ***online due to COVID-19*** 2nd Term

AY 20-21

Exposure Assessment Techniques for Health Risk Management

AY 19-20 3rd Term

3 credit graduate course, in-person and online

Environmental Hazards and Health Risks

Fall Semester 2019

3 credit undergraduate course, in-person

Service

BSPH Virtual Teaching and Education Committee (VTEC) Member **May 2020 to May 2021**

- In response to COVID-19 and all academic activities moving to a virtual platform, this group of faculty, students, staff, and administrators, led by Dean Ellen MacKenzie, formed to maintain a high-quality teaching and learning experience that optimizes student engagement for all students regardless of where they are located. As the Student Assembly representative, my role was to provide the group with perspectives on student needs, problems, concerns, issues, and general input on future plans in our virtual learning community.

BSPH Student Assembly **May 2019 to May 2021**

- Student Assembly represents, preserves, and promotes the interests of all students at the Bloomberg School of Public Health.

Vice President

May 2020 to May 2021

- As Vice President, I serve as the main support to the SA President and primary coordinator/manager of the various SA committees and their respective vice presidents. My duties in this role involve:
 1. Presiding over SA meetings in the absence of the President;
 2. Serve as an ex-officio member of standing committees and ad-hoc committees of the SA;
 3. Serve as the SA office manager;
 4. Assume the duties of other SA Executive Officers when there are vacancies in those officer positions;
 5. Serve as the SA rep of various school- and university-wide committees as needed.

Member at Large

May 2019 to May 2020

- As a Member at Large, I act as a liaison between various student groups and Bloomberg School administration.
- Served as the Environmental Health and Engineering Department Representative to the board (2019-2020 academic year) to ensure EHE students' ideas, concerns, and interests were represented.

BSPH Student Section AIHA **August 2018 to May 2021**

- Increase knowledge of industrial hygiene and occupational health and safety within the JHU Bloomberg community
- Promote the profession and cooperate with local AIHA sections to advance student growth and connections

President

August 2018 to May 2021

- As President, my duties in this role involve:
 1. Representing or delegating representation of the Student AIHA to the EHE Department, School, University, local, state, national, and international agencies and organizations;
 2. Presiding over meetings;
 3. Providing connections between the Student Section and Local AIHA Sections and AIHA National.

Environmental Health and Engineering Student Organization Member **August 2018 to May 2021**

- EHESO serves to facilitate social, intellectual, and service-oriented interaction between students, staff, and faculty of the Department of Environmental Health and Engineering.

- Served as the EHESO Representative to the EHE Department Educational Programs Committee (AY 2020-2021) to ensure EHE students' ideas, concerns, and interests were represented.
- Served as the EHESO Representative to the Student Assembly (AY 2019-2020) to ensure EHE students' ideas, concerns, and interests were represented.

Silver Spring Library Advisory Committee Member **October 2017 to August 2018**

- Advise the Montgomery County Library Board and the Library Manager on issues of local interest and concern for the benefit of the community and Montgomery County Public Libraries

United Therapeutics First Responder Team Member **March 2017 to July 2018**

- Provide support, including first aid and CPR, during emergencies to those affected by the incidents.

AIHA Potomac Section **March 2017 to present**

- Protect the health and safety of workers and the community
- Increase knowledge of industrial hygiene and occupational health and safety in a specific region
- Promote the profession and cooperate with government, industrial, educational, and other professional bodies

Board Member – Member at Large *June 2018 to June 2020*

- As a Member at Large, I act as a liaison between various working groups within the Potomac Section and the local and national AIHA chapters.
- Support the needs of the Potomac Section Board regarding meeting and event organization.

School of Public Health Student Advisory Committee Member **September 2014 to May 2015**

- Provide the Dean with student perspectives on school-wide needs, problems, concerns, issues, and general input on future plans.

Epsilon Sigma Alpha, Psi Mu Chapter, University of Pittsburgh **January 2011 – April 2012**

- Member of the inaugural chapter at the University of Pittsburgh, which now has over 90 student members.
- Co-ed service fraternity serving the local Pittsburgh and University communities with the purpose of “inspiring leadership and service by bringing good people together to pursue programs and projects that make a positive difference locally, nationally, and internationally.”
- The main philanthropic recipient is St. Jude’s Children’s Hospital.

Awards and Honors

AIHA Exposure Assessment Strategies Committee Best Poster Award for *Using variations of the well-mixed room model to assess chemical exposures*. AIHce, May 2020.

Kazuyoshi Kawata Fund in Sanitary Engineering and Science Fund provides support for students with a focus in sanitary engineering and science in the Department of Environmental Health Sciences. Dr. Kawata served on the faculty at the Johns Hopkins Bloomberg School of Public Health from 1966-1989. He is regarded as an international expert, professional engineer, educator and consultant in environmental engineering and environmental health. Academic Year 2019.

The Dr. C. W. Kruse Memorial Fund is in honor of Dr. Krusé, who served as chair of the Departments of Sanitary Engineering (1962-1963) and Environmental Health Sciences (1966-1976). This award, established by his colleagues, friends, and former students, recognizes academic achievement. Academic Year 2019.

The David Leslie Swift Fund in Environmental Health Engineering Fund was established in 1998 by Suzanne Swift in honor of her late husband David Leslie Swift, PhD. Dr. Swift was a faculty member at the School from 1966 to 1997. His research career was distinguished and diverse, and his work on the health effects of particulate matter and air pollutants made him a pioneer in his field. This fund supports exceptional masters, doctoral, or postdoctoral students in the Division of Environmental Health Engineering of the Department of Environmental Health Sciences. Academic Year 2019.

United Therapeutics Women in Manufacturing program aimed at supporting, promoting, and inspiring women at UT who work in manufacturing. This group encourages female UT manufacturing employees to share perspectives, develop information channels, and improve leadership and communication skills. January 2018.

Federal Service Excellence Award for outstanding performance in the scientific, medical, or engineering project team category. This award recognizes the exceptional efforts and professional demeanor which not only reflects a sincere interest in duties and responsibilities but also clearly demonstrates the desire to assist in improving the Federal Government and citizens it serves. April 2017.

NIOSH Rising Star program for NIOSH employees who have demonstrated commitment to self-improvement and advancement of their knowledge and skills in the field of occupational safety and health research. October 2016 through February 2017.

University of Maryland School of Public Health Dean's Graduate Scholar Award for excelling academically, demonstrating curiosity, maturity, creativity, motivation and intellect while contributing to the SPH community and greater surrounding community as a whole. May 2015.

Publications

Fox M, **Babik K**, et al. (2019). Review of First Responder Health and Worker's Compensation Claim Requirements. Tech rp. part of the VA Joint Legislative Audit and Review Commission's of *Review of Virginia's workers' compensation system and use of disease presumptions*. (JLARC Report No. 530-1). <http://jlarc.virginia.gov/landing-2019-workers-compensation.asp>

Smyth EM, Chattopadhyay S, **Babik KR**, et al. (2019). The Bacterial Communities of Little Cigars and Cigarillos Are Dynamic Over Time and Varying Storage Conditions. *Front. Microbiol.* 10:2371.

doi: 10.3389/fmicb.2019.02371.

Chattopadhyay S, Smyth EM, Kulkarni P, **Babik KR**, et al. (2019). Little cigars and cigarillos harbor diverse bacterial communities that differ between the tobacco and the wrapper. *PLoS One* 14(2): e0211705. doi: 10.1371/journal.pone.0211705.

Brame J, Alberts Erik, Schubauer-Berigan M, Dunn K, **Babik K**, et al. (2018). Using Life Cycle Assessment to Guide Nanomaterial Release & Exposure Potential from a Carbon Nanotube-enabled Anti-corrosive Coating. *NanoImpact* 12(58-68). doi: 10.1016/j.impact.2018.10.002.

Babik KR, Shockey T, Moore L, Wurzelbacher SJ (2018). Standardizing industrial hygiene data collection forms used by workers' compensation insurers. *JOEH* 15(6). doi: 10.1080/15459624.2018.1490022

Shockey T, **Babik KR**, Moore L, Wurzelbacher SJ (2018). Determining Industrial Hygiene Data Collection, Storage, and Usage Among State-Based and Private Workers' Compensation Insurers. *JOEH* 15(6). doi: 10.1080/15459624.2018.1453140.

Fent KW, Evans DE, **Babik KR**, et al. (2018). Air Concentrations of Contaminants During Controlled Residential Fires. JOEH 15(3). doi: 10.1080/15459624.2018.1445260.

Babik KR, Dahm MM, Dunn, KH, Dunn KL, Schubauer-Berigan MK (2018). Characterizing workforces exposed to current and emerging non-carbonaceous nanomaterials in the U.S. JOEH 15(1). doi:10.1080/15459624.2017.1376252.

Chopyk J, Chattopadhyay S, Kulkarni P, Claye E, **Babik KR**, et al. (2017). Mentholation affects the cigarette microbiota by selecting for bacteria resistant to harsh environmental conditions and selecting against potential bacterial pathogens. Microbiome 5(22). doi: 10.1186/s40168-017-0235-0

Boyle MD, Payne-Sturges DC, Sangaramoorthy T, Wilson S, Nachman KE, **Babik K**, et al. (2016). Hazard Ranking Methodology for Assessing Health Impacts of Unconventional Natural Gas Development and Production: The Maryland Case Study. PLoS ONE 11(1): e0145368. doi:10.1371/journal.pone.0145368

Milton DK, Wilson S, Jiang C, Dalemarre L, Sapkota A, Sangaramoorthy T, Boyle MD, Nachman KE, **Babik K**, et al. (2014). Potential Public Health Impacts of Natural Gas Development and Production in the Marcellus Shale in Western Maryland. University of Maryland School of Public Health: Prepared for the Maryland Department of the Environment and the Maryland Department of Health and Mental Hygiene. <http://www.marcellushealth.org/final-report.html>.

Posters and Presentations

—
Babik KR, Edmondson M. Mathematical Modeling Approaches to Managing Workplace Health and Safety. Technical Presentation: AIHce. Dallas, TX. May 2021. ***Online due to COVID-19***

Babik KR, Das D, Ramachandran G. Assessment of Aerosol Transport and Ventilation Systems in Public Transit Rail Cars Under Static and Dynamic Conditions. Poster Session: AIHce. Dallas, TX. May 2021. ***Online due to COVID-19***

Babik KR, Das D, Shao Y, Ramachandran G. Using variations of the well-mixed room model to assess chemical exposures. Poster Session: AIHce. Atlanta, GA. May 2020. ***Online due to COVID-19***

Received Exposure Assessment Strategies Committee Best Poster Award

Babik KR, Shockey T, Moore L, Wurzelbacher SJ. Standardizing industrial hygiene data collection forms used by workers' compensation insurers. Poster Session: AIHce. Minneapolis, MN. May 2019.

Babik KR, Dahm MM, Dunn, KH, Dunn KL, Schubauer-Berigan MK. Characterizing workforces exposed to current and emerging non-carbonaceous nanomaterials in the U.S. Lecture: Potomac Section of AIHA Professional Development Seminar. Rockville, MD. February 2018.

Babik KR, Dahm MM, Dunn, KH, Dunn KL, Schubauer-Berigan MK. Characterizing workforces exposed to current and emerging non-carbonaceous nanomaterials in the U.S. Poster Session: AIHce. Seattle, WA. June 2017.

Babik KR, Dahm, MM, Dunn KL, Schubauer-Berigan MK. Methods for Gathering Information on Nanomaterial Companies in Two Studies. Poster Session: NTRC 2016 Science Meeting. Morgantown, WV. April 2016.

Babik KR, Fagan K, Hodgson M. Using OSHA Information System to Evaluate Data Collected During the Isocyanate National Emphasis Program. Poster Session: Public Health Research @ Maryland. College Park, MD. April 2014.

Skills

- Certified industrial wastewater operator-in-training
- Various vendor-specific software related to industrial hygiene monitoring equipment including direct-reading instruments
- Questionnaire and survey development
- STATA Statistical Software
- R Statistical Software