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COVID-19 Public Transportation Air Circulation and Virus Mitigation Study

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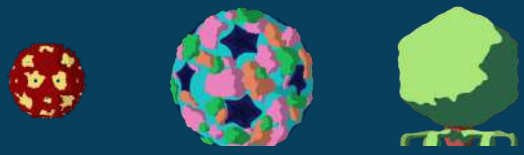
Air Circulation

Social distancing alone may not work on buses. The virus spreads throughout the bus in seconds and takes minutes to clear. Without proper precautions, airflow in buses could make transit ridership risky.

If the bus has dual HVAC systems, physical separation of the driver space (e.g. using a clear plastic sheet) can be effective in protecting the driver, especially with positive pressure in the driver cabin.

The air should be cleaned, to be safe.

Mitigating the Virus



MS2 Virus | Phi 6 Virus | T7 Virus

Similar to Coronavirus

3 different (bacteriophage) viruses were used to assess the efficacy of different technologies. Viruses were measured in the air and on surfaces.

Effective Technologies

Photocatalytic Oxidation

UV-C Lights

Both technologies will protect passengers and drivers from both the coronavirus and other air-borne viruses, such as the flu. These technologies would be valuable in post-corona times.

ONLY effective after the virus enters the HVAC.

Face masks should be worn. They are the first line of defense.

Mineta Transportation Institute

Founded in 1991, the Mineta Transportation Institute (MTI), an organized research and training unit in partnership with the Lucas College and Graduate School of Business at San José State University (SJSU), increases mobility for all by improving the safety, efficiency, accessibility, and convenience of our nation's transportation system. Through research, education, workforce development, and technology transfer, we help create a connected world. MTI leads the Mineta Consortium for Transportation Mobility (MCTM) funded by the U.S. Department of Transportation and the California State University Transportation Consortium (CSUTC) funded by the State of California through Senate Bill 1. MTI focuses on three primary responsibilities:

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Report 22-08

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16. Abstract

COVID-19 may have forever changed our world. Given the limited space and air circulation, potential infections on public transportation could be concernedly high. Accordingly, this study has two objectives: (1) to understand air circulation patterns inside the cabins of buses; and (2) to test the impact of different technologies in mitigating viruses from the air and on surfaces inside bus cabins. For the first objective, different devices, metrics and experiments (including colored smoke; videotaping; anemometers; pressure differentials; particle counts; and 3D numerical simulation models) were utilized and implemented to understand and quantify air circulation inside different buses, with different characteristics, and under different operating conditions (e.g. with windows open and shut). For the second objective, three different live prokaryotic viruses were utilized: Phi6, MS2 and T7. Various technologies (including positive pressure environment inside the cabin, HEPA filters with different MERV ratings, concentrated UV exposure with charged carbon filters in the HVAC systems, center point photocatalytic oxidation technology, ionization, and surface antiviral agents) were tested to evaluate the potential of mitigating COVID-19 infections via air and surfaces in public transportation. The effectiveness of these technologies on the three live viruses was tested in both the lab and in buses in the field. The results of the first objective experiments indicated the efficiency of HVAC system designs, where the speed of air spread was consistently much faster than the speed of air clearing. Hence, indicating the need for additional virus mitigation from the cabin. Results of the second objective experiments indicated that photocatalytic oxidation inserts and UVC lights were the most efficient in mitigating viruses from the air. On the other hand, positive pressure mitigated all viruses from surfaces; however, copper foil tape and fabrics with a high percentage of copper mitigated only the Phi6 virus from surfaces. High-temperature heating was also found to be highly effective in mitigating the different viruses from the vehicle cabin. Finally, limited exploratory experiments to test possible toxic by-products of photocatalytic oxidation and UVC lights inside the bus cabin did not detect any increase in levels of formaldehyde, ozone, or volatile organic compounds. Implementation of these findings in transit buses, in addition to the use of personal protective equipment, could be significantly valuable for protection of passengers and drivers on public transportation modes, possibly against all forms of air-borne viruses.

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CFD: Computational fluid dynamic modeling

CNG: Compressed Natural Gas fuel

HVAC: Heating, Ventilation, and Air Conditioning

OEM: Original equipment manufacturer

SARS-CoV-2: Name given the novel coronavirus strain that causes COVID-19 disease

Executive Summary

In May 2020, a research team led by Fresno State Transportation Institute partnered with Fresno County Rural Transit Agency and Clovis Transit in Fresno County to perform a time and budget-constrained pilot study on the possible risks of infection by the novel coronavirus that causes COVID-19 disease as well as the methods to mitigate those risks on transit buses. The research team included members from California State University, Fresno; the University of California, Merced; Fresno Metro Ministry, a community advocacy organization in Fresno; and a private heating, ventilation, and air conditioning (HVAC) engineering firm, Air2O Cooling.

The research team had two objectives:

1) to understand and model air circulation in the passenger and driver spaces of public transit buses under different operation conditions, with a focus on how that circulation impacts potential viral spread, and

2) to evaluate the effectiveness of different technologies in mitigating the risks of infection of passengers and drivers from viruses released into the interior spaces of the bus via virus aerial circulation or settling on surfaces.

For the first objective, the team studied the airflow within the respective agency buses using actual airflow measurements from the bus HVAC systems. Moreover, non-toxic colored smoke and steam were released inside the buses to visually observe and record the airflow movement. Testing was done with colored smoke and steam under various operational conditions such as vehicles in motion at highway speeds or sitting still, windows open and closed, vehicle door(s) open and shut, HVAC system on and off, HVAC fresh air on and off, emergency hatch open and shut, and with the source of spread at different locations on the vehicle. The times it took to fill the buses with smoke and then clear the space were recorded. Additionally, computational fluid dynamic models (CFD) were developed for the different vehicles investigated.

The results of the airflow study show that the existing HVAC systems in transit buses are very effective in moving air-conditioned air quickly within the passenger and driver areas, and in maintaining that air in vehicles for long periods of time, as they are designed to do. However, this fast and effective movement of air creates a high level of risk of infection from an airborne viral agent released inside a transit bus such as the novel coronavirus. Particularly concerning was the much slower speed of air clearance from the vehicle cabin. The study points to the need for viral mitigation technologies to be retrofitted into the existing bus HVAC systems and potentially new systems to be developed and incorporated into buses in the future.

For the second objective, the team investigated the efficiency of different methods and technologies in mitigating the virus from the air and surfaces. The team utilized three live bacteriophage viruses with different resemblance characteristics to the novel coronavirus: Phi6,

MS2 and T7. The team examined the efficiency of the tested technologies both in the lab as well as on buses in the field. The tested technologies included: cooling, heating, carbon filter, HEPA filters, UVC lights, photocatalytic oxidation, ionization, positive pressure, and antiviral materials and fabrics.

Findings of the virus mitigation study demonstrated comforting levels of consistency between the results of both the lab and field experiments. Photocatalytic oxidation inserts and UVC lights were found to be the most effective in mitigating the different virus types from the air. On the other hand, the creation of a positive pressure environment (0.5-inch water column) mitigated all viruses on surfaces. Also, copper foil tape and fabrics with a high percentage of copper mitigated the Phi6 virus; however, the results were inconclusive with the other two viruses.

Following the completion of this project, the team received concerns about the possible release of toxic by-products into the vehicle cabins when using the photocatalytic oxidation inserts and UVC lights technologies. Accordingly, the team conducted limited exploratory experiments to measure the levels of formaldehydes, ozone, and volatile organic compounds inside the cabins of the vehicles with these technologies absent and installed within the bus HVAC system. The team conducted a few experiments while the buses were static and in motion. The experiments did not detect any increase in the levels of formaldehyde, ozone, or volatile organic compounds inside the bus cabin.

It is worth noting that retrofitting these technologies into the bus HVAC systems would mitigate air-borne viruses distributed by the HVAC system. These technologies would not, however, mitigate the airborne viruses while traveling from the viral source to the intake of the HVAC system. Accordingly, these technologies do not eliminate the value of using personal protective equipment (e.g. facial masks) by both passengers and drivers.

Proper implementation of these findings in transit buses (and potentially other similarly confined spaces with HVAC systems) could be significantly valuable and directly lead to improved protection of passengers and drivers on public transportation modes—possibly against all forms of air-borne viruses.

1. Introduction and Motivation

In mid-May 2020, when this study was first begun, infection rates from the novel coronavirus that causes COVID-19 disease continued to climb in the United States and around the world, leading many health and government officials to conclude that there would be no "return to normal" unless an effective vaccine was developed and administered broadly across the global population. While the early focus on virus transmission centered on contaminated surfaces and making sure hands were washed properly, research emerged showing increasing evidence that the virus was airborne and could be transmitted through aerosol particles that linger in stagnant air.

At that time, with an effective vaccine months away from being approved for use—and much time needed for it to be produced in a volume large enough to vaccinate billions of people—wearing a protective mask became the standard piece of apparel for everyone in nearly every aspect of life involving human interaction, especially in confined spaces. Analysis of the efficiency of the SARS-CoV-2 coronavirus in infecting humans led researchers around the world to the conclusion that the virus would not be going away any time soon, making research into how to protect people from infection as they go about their daily lives a question of critical importance.

As evidence of airborne transmission risk increased, shared transportation and transit vehicles gained more attention as potential places for infection due to the confined spaces of passenger seating, a relatively enclosed environment, and heating and air conditioning systems that recirculate the interior air. Without definitive evidence that public transit and shared mobility services could be made safe for riders and drivers from COVID-19 infection, the public would of course be reluctant to return to using these services. Moreover, the services themselves were at risk due to the expected loss of revenue from ridership.

Accordingly, this study aimed to assess the risk of COVID-19 infection for drivers and passengers in transit buses and to identify effective and cost-efficient solutions to mitigate such risk.

2. Literature Review

Numerous reports describe the risk of contracting respiratory viruses, including COVID-19, while using public transit (Abdullah et al., 2020; Shen et al., 2020; Sun and Zhai, 2020; Yilmazkuday, 2020). This might be because public transport vehicles are confined spaces where the risk of human-to-human airborne virus transmission is high (Sun and Zhai, 2020). In addition, as a result of the lengthy exposure time window and the structural characteristics of vehicles during public transport travel, the spread of infection could be extremely rapid. Consequently, providing safety countermeasures to prevent and control the spread of COVID-19 based on the characteristics of public transportation is necessary.

Early works in this area focused primarily on quantifying the transmission risk of COVID-19 on different public transportation modes, including buses (Chen et al., 2020), trains (Hu et al., 2020; Zhao et al., 2020b), airplanes (Abdullah et al., 2020; Associated Press, 2020), and ships. Hu et al., (2020) studied the transmission risk (attack rate) of COVID-19 on high-speed train passengers in China by analyzing the spatial and temporal distribution of COVID-19 transmission among train passengers. Their results indicated that passengers seated within a distance of 3 rows and 5 columns of the patient zero (index case) have an attack rate between 0 to 10.3%. In addition, passengers seated on the same row as patient zero have an average attack rate of 1.5%, which is higher than the passenger attack rate of those seated in the other rows. Their estimation demonstrated that the attack rate declined with increasing distance but increased on average by 0.15% per hour of co-travel.

Additionally, travelers adjacent to patient zero had the highest attack rate compared to all other seats considered. Twenty-five passengers diagnosed with COVID-19 boarding a flight from Moscow to Beijing on April 8th revealed that the airplane cabin and its air circulation system were not immune to virus spreading (Shen et al., 2020). One possible explanation for the high risk of airborne infection is that the microorganisms' transmission in the cabin is influenced by factors such as exhaust ventilation, turbulent diffusion, and adventive velocity (Gupta et al., 2012). Early studies on transmissions of COVID-19 aboard the Diamond Princess cruise ship quantified that the mean reproduction number (R0) in the confined cabin situation can be increased to 11, which is substantially higher than the average estimation associated with community-level transmission dynamics in China (Liu et al., 2020; Mizumoto et al., 2020; Mizumoto and Chowell, 2020; Moriarty et al., 2020; Zhao et al., 2020a).

Few studies have focused on COVID-19 transmission on multiple different transportation modes. For example, Sun and Zhai (2020) compared infection risk on three main public transportation modes (public buses, high-speed trains, and airplanes) based on worldwide collected critical data from several actual pandemic cases. Their results showed that public buses had the highest risk of infection among all public transportation vehicles. These results are expected because, when

compared to other public vehicles, buses have lower air distribution effectiveness, a lower fresh air rate, and higher occupancy density.

Historically, during an evolving outbreak or pandemic, non-pharmaceutical interventions (NPIs) like physical distance, isolation, and mask use have been potential solutions to flattening the peak of infection rates in communities (Seale et al., 2020). Moreover, several recent COVID-19 studies have warned that close contact must be avoided because of virus transmission via droplets and airborne routes through respiratory activity (Howard et al., 2020; Hsiao et al., 2020; Peng et al., 2020; Radio, 2020; Shereen et al., 2020). Consequently, transportation decision-makers in the US and around the world have tried to apply rules and restrictions based on NPI's. Sun and Zhai (2020) conducted a study on the effect of NPI's on COVID-19 transmission on different public transportation modes. They proposed two critical indices of social distance probability (Pd) and ventilation effectiveness (Ez) into the Wells-Riley predictive method to predict the infection probability of COVID-19. Their results briefly indicated that (1) the infection probability for most of the tested transportation modes at the end of the first 30 minutes can be decreased by 18.8 to 28.2, and (2) a 50% reduction in the occupancy density of high-speed trains, public buses, and subways leads to a decrease in the risk of infection after 30 minutes by 9.1%, 3.2%, and 2.5%, respectively.

Although NPI approaches may flatten the peak of COVID-19 infection rates within communities, they cannot guarantee a near-elimination of the infection probability, as these strategies rely upon community understanding of interventions and the motivation to engage. Moreover, face coverings and travel restrictions are likely to provide only limited protection. Other measures will be needed to ensure people's safety (Abdullah et al., 2020; An Independent, 2020). To this point, researchers have been working on novel methods such as antiviral coating, pharmaceutical nanotechnology, and surface design technologies. Reducing common touch surfaces and expanding touch/hands-free options are some of the suggested strategies to decrease the spread of COVID-19 (Hom, 2020). For example, integrating speech-recognition technology with visual displays can facilitate touch-free transactions at kiosks. It is also suggested that bus passengers should be able to use mobile devices and chip card passes, which are contactless ways for passengers to "schedule" or "signal" their vehicle to pull over at their desired stops (Hom, 2020).

Eliminating all touch surfaces, however, is not possible due to safety concerns (e.g., seats, handrails, and poles). Consequently, using materials with antimicrobial properties such as copper and its alloys can be effective in reducing surface contamination. In contrast to commonly used stainless steel and plastic surfaces in transportation systems, copper surfaces can mitigate many types of viruses immediately (Noyce et al., 2007; Saha et al., 2016). Copper has been found to mitigate COVID-19 virus in four hours (Van Doremalen et al., 2020). In addition to chemical disinfectants, far Ultraviolet C light (207-222 nm wavelength) can be used to neutralize many pathogens in the air and on many different surfaces (Welch et al., 2018). Recently, in China, buses are disinfected through a combination of UV tunnels and portable UV lights. Using this approach reduces disinfection times from 40 minutes (based on the traditional spray and wipe methods) to

around 7 minutes (Corbishley, 2020; Sustainable Bus, 2020). Although the application of UV-C in US public transportation is limited, the Metropolitan Transportation Authority in New York announced the implementation of a pilot program using UV-C technology in mid-May 2020 (Airport International, 2020).

3. Research Objectives

The general objectives of this research project were two-fold:

1) to understand and model air circulation, particularly the speed of air spreading and clearing, in the passenger and driver spaces of public transit buses, and

2) to evaluate potential mitigation technologies and/or protocols to reduce the risk of (aerial and surface) infection of passengers and drivers from viruses released into the interior spaces of the bus.

The following sections of this report provide a description of the work executed and findings of these two objectives.

4. Part 1: Airflow Study

The first objective of this work, understanding and modeling air circulation inside the interior spaces of public transit buses, relied on two main measures that were investigated under different conditions and modes of operation. The two main measures were:

a) Spread: understanding how a virus spreads inside the cabin of the bus (e.g. how fast and in which direction)

b) Clear: understanding how a virus will clear after spreading inside the bus (e.g. would the opening of the bus door at bus stops be sufficient)

These main measures were investigated under the following conditions and modes of operation:

- Vehicle Configuration: understanding the difference, if any, in airflow between different sizes and configurations of transit buses.
- Motion: understanding the difference in airflow between static and in-motion operation of buses.
- Windows: understanding how opening or closing windows on buses impacts airflow when the vehicle is in-motion or static.
- Door: understanding how opening the bus door at stops or stations changes airflow within the bus and/or risk to passengers entering the bus.
- Emergency Hatch: examining the possible impact of operating the bus with the roof emergency hatch open.
- HVAC: understanding how the different modes of HVAC operation (off, fresh air only, and air circulation with conditioned air) affect airflow and circulation inside the cabin of a bus.
- Onset Location: understanding how the virus onset location (front, middle, or rear of the bus) may impact virus circulation in the bus cabin.

The ultimate goal for the airflow study was to inform transit agencies and bus manufacturers about how HVAC systems in buses may need to be designed and/or retrofitted with anti-viral technology to mitigate the risk of COVID-19 infection - and potentially other air-borne viral diseases, e.g. influenza.

4.1 Research Approach

For this project, the research team worked with two transit agencies in the San Joaquin Valley of California: Clovis Transit and Fresno County Rural Transit Agency (FCRTA) in Fresno County. Five (5) different buses were used for testing and covered a range of transit bus designs from 26-foot cutaways with dual HVAC systems (using the chassis OEM's HVAC system for the driver and a separate body HVAC system for passengers) to 40-foot coaches with a fully integrated HVAC system supplying both the driver and passengers. The different buses investigated were electric, CNG, and diesel operated and had different HVAC and seating configurations.

The majority of testing was done on two different 35-foot transit coaches with fully integrated HVAC systems owned by FCRTA; one with a rear-mounted HVAC system with a return air duct in the back wall over the rear passenger seats and one with a roof-mounted HVAC system with return air ducting in the ceiling over wheel chair positions just behind the front axle. Both of these bus designs used continuous supply air ducting in the ceiling next to the windows with slots over every passenger row in the bus. The driver's air supply was supplied by multiple, adjustable vents over the driver's seating position in the front of the bus supplied by the same ducting as the passengers. The integrated nature of these HVAC systems was important for the study since there is currently no way to segregate airflow from the HVAC on these designs to provide a separate air supply to drivers and passengers; therefore, any airborne virus released inside the coach could impact all occupants if transported by the HVAC system. The interiors of these two buses are presented in Figure 1.

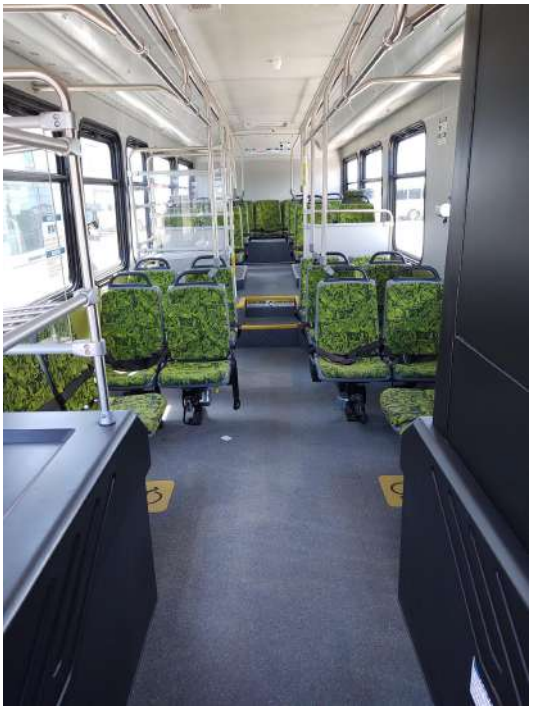
Three main technologies were adopted to capture air circulation inside the buses:

1) Using hand-held airspeed meters (anemometers), where air speed was measured at numerous locations inside the bus cabins (Figure 2).

2) Colored smoke candles, where colored smoke was released at different locations in the buses and video recordings were captured to compute speeds and directions of air circulation (Figure 3, Figure 4).

3) Steam machines, similar to the colored smoke, where white steam was released at different locations in the buses and video recordings were captured to compute speeds and directions of air circulation (Figure 5, Figure 6). Advantages of steam over smoke include that its density and behavior is closer to human breath than smoke.

In addition to the above, other measurements included air pressure differences, temperature and humidity readings, and air particulate counts. Based on these different readings and measurements, computational fluid dynamics models were constructed for different vehicle operation scenarios using the ANSYS Fluent software.



Interior of Bus B

Interior of Bus A

Figure 1. Interiors of Two of the Investigated Buses

Figure 2. Airspeed from HVAC Ducting being Measured

Figure 3. Non-Toxic Colored Smoke Exhausting from Bus A

All in-motion testing was done on a freeway with speeds of between 50 and 60 miles per hour, as FCRTA operates intercity bus service with the 35-foot coaches being tested. This study utilized multiple devices during each test to capture data.

Different measurements were recorded for the various vehicle operation conditions being investigated. The following is a list of the primary testing approaches and measurements that were captured and utilized to benchmark the system performance under different scenarios:

- Airflow and circulation inside the buses were captured using non-toxic smoke candles and a steam generation machine, which are common in the HVAC industry.
- Airflow (smoke/steam) movements were recorded and timed using several video cameras inside the cabin (Figure 6).
- Airflow and circulation inside the buses were modeled via CFD models under different vehicle motion scenarios (e.g. stationary and in motion).
- Pressure differentials between inside and outside the cabin were measured to investigate the possibility of adopting a positive pressure strategy to potentially mitigate virus circulation inside the cabin.
- A particle counter was utilized to measure physical particles in the air at different locations and at different heights.

- Temperatures and relative humidity were measured throughout the bus cabin.
- Carbon monoxide concentrations were measured at different locations inside the cabin.

Two main rounds of testing were implemented:

- The first round of tests focused on understanding air circulation differences between the different buses while the vehicles were stationary and all windows and doors were closed. It examined air circulation inside five different types of buses (using anemometers, colored smoke, white steam, where all tests were documented using video recording) to understand possible differences in flow patterns attributable to different HVAC arrangements. The five buses came from different manufacturers and use different energy sources (electric, CNG, and diesel) and have different sized interior spaces, seating, and HVAC arrangements (Figure 1).
- The second round of tests focused on understanding air circulation differences that may be attributable to differences in vehicle conditions and modes of operation. This round of air circulation testing was done inside the passenger compartment of the two 35-foot rural transit coach buses. The explored conditions and modes of operation included the bus stationary and in motion, with windows shut and open, with smoke disseminating from the rear and front of the bus, with HVAC on and off, with HVAC fresh air on and off, and with the emergency hatch open and shut.

The different measures recorded in these two rounds of experiments were utilized to develop computational fluid dynamic models, which are explained in the following section. Additionally, the conclusion of these two rounds of airflow tests prepared the way for live virus testing in the same two buses to explore the effectiveness of various technologies and anti-viral materials for both surface application and retrofit into the HVAC system. This is further explained in the Part 2, Virus Mitigation Study.

Figure 4: Interior Bus B, Smoke Testing

Figure 5: Interior Bus A, Steam Testing Photo

Figure 6: Video Recording of Steam Circulation in Moving Bus

4.2. CFD Models

This section presents details of the CFD models developed for the airflow circulation inside the investigated buses.

4.2.1 Background

Airflow and circulation patterns inside buses were numerically simulated for two different types of 35-foot rural transit buses and to capture the conditions in the bus cabin under different vehicle motion scenarios (e.g., stationary (windows shut) and in motion (windows open)). Bus A is CNG powered, and its return air duct is located at the back of the passenger compartment on the rear wall over the rear seats, whereas Bus B is an electric bus, and its return air ducts are located in the ceiling over the wheelchair positions behind the front axle close to the driver station. Both buses' supply air outlets are similar to each other in structure and design. In addition, airflow and circulation patterns inside the buses were also numerically simulated for two different types of city transit buses and to capture conditions in the bus cabin under the stationary (windows shut)

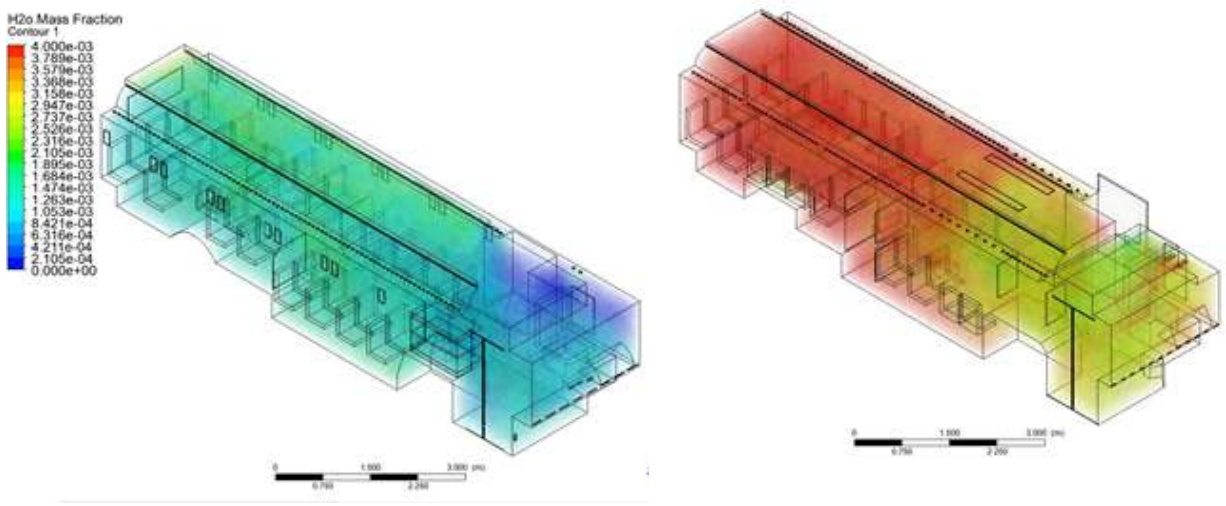
scenario only. Bus C is a 20-foot CNG-powered city transit bus, and both of its supply and return air ducts are located in the ceiling over the middle-back of the passenger compartment. Bus D is a 15-foot electric-powered city transit bus, and both of its supply and return air ducts are located in the ceiling over the rear seats.

The present work employs numerical techniques and aims to understand and model air circulation patterns inside the cabins of different bus configurations and conditions. The numerical simulations will be compared with the smoke experiments, if available. The interior geometries of the buses are profiled, including driver and passengers' seats, windows, supply air diffusers/slots, exhaust grilles, stairs, driver's dashboard, and storage area. The supply air diffusers/slots and exhaust grilles are included in the numerical study. The numerical three-dimensional flow visualizations and air circulation patterns over time inside the bus will be presented. The present work utilizes the computational fluid dynamics software ANSYS Fluent to simulate the airflow numerically.

4.2.2 Rural Transit Bus Configurations

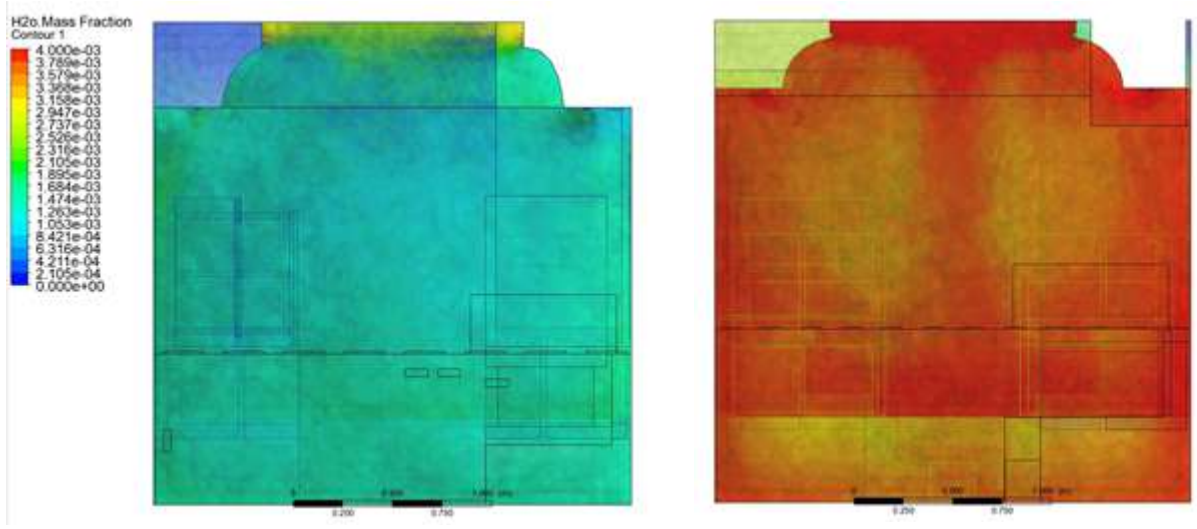
Figure 7 compares the airflow and circulation patterns traced by water vapor mass fractions inside the stationary buses A and B at about 28 seconds numerically. For Bus A, the location of the return air grille is at the back of the passenger compartment on the rear wall over the rear seats, whereas Bus B's return air ducts are located in the ceiling over the wheelchair positions behind the front axle close to the driver station. The supply air diffusers are similar in design and structure for both buses. Both buses are around 9 m long, 2.5 m wide, and 1.5 m tall. The numerical smoke plumes were observed concentrating towards the middle and back of both buses and moving towards the front of the buses. Bus B generally possessed higher mass fractions of water vapor compared with Bus A.

Figure 8 thru Figure 10 compare the steam distributions traced by numerical water vapor mass fractions and experimental smoke, as well as steam visualizations from the front of the stationary buses. Both methods display the plumes moving from the ceiling of the bus cabin towards its floors and forming the air circulation. The numerical and experimental visualizations demonstrate qualitative agreement between each other. In addition, the CFD predictions of the return airspeeds for both buses A and B have reasonable agreement with the experimental data. The CFD models are capable of capturing the flow phenomena and flow measurements from the field tests.



(a) Bus A (b) Bus B

Figure 7. Comparison of Numerical Steam Distributions Traced by Water Vapor Mass Fractions Inside the Stationary Buses (A) Bus A and (B) Bus B at Around 28 Seconds



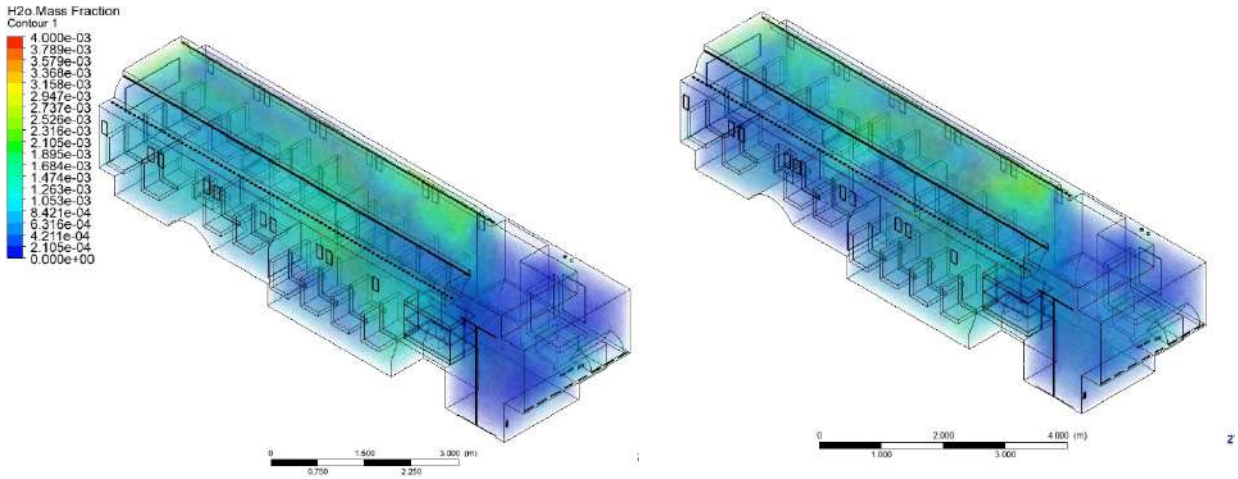
(a) Bus A (b) Bus B

Figure 8. Comparison of Numerical Steam Flow Patterns Traced by Water Vapor Mass Fractions Viewing from the Front of the Stationary Buses (Bus A And B) at Around 28 Sec

Figure 9. Experimental Smoke Sisualization of the Interior Stationary Bus A Viewing from the Front

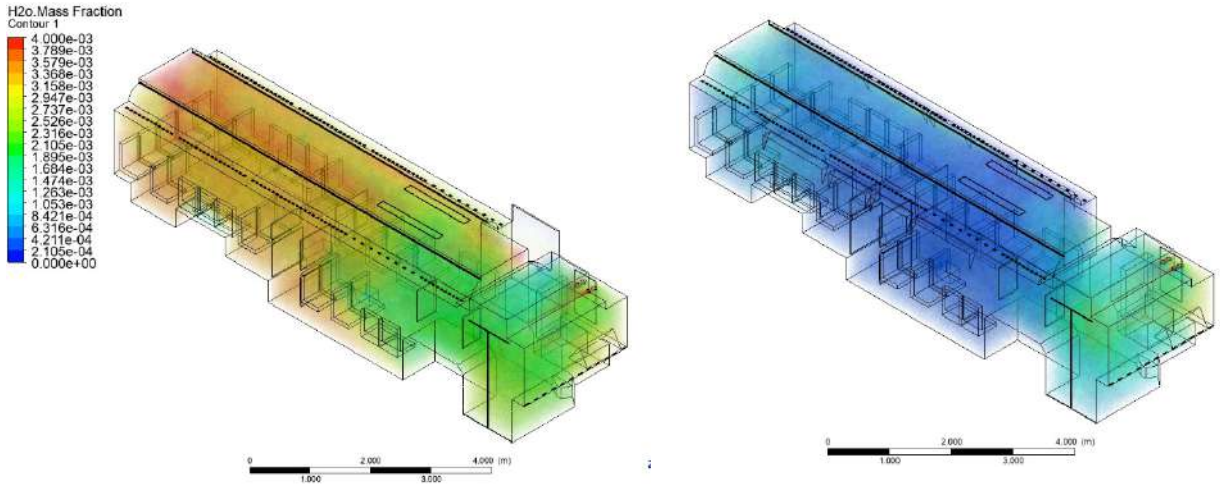
Figure 10. Experimental Steam Visualization of the Interior Stationary Bus A Viewing from the Front

Figure 11 and Figure 12 compare the numerical steam distributions under vehicle motion scenarios of stationary (windows shut) and in motion (windows open) for Buses A and B, respectively. The steam was generally diluted when the bus was in motion compared with when it was stationary, especially for Bus B. When the bus was in motion, the time to spread was found to be significantly less compared to when it is stationary. Such is consistent with the experimental observation.



(a) Stationary (Windows Shut) (b) Motion (Windows Open)

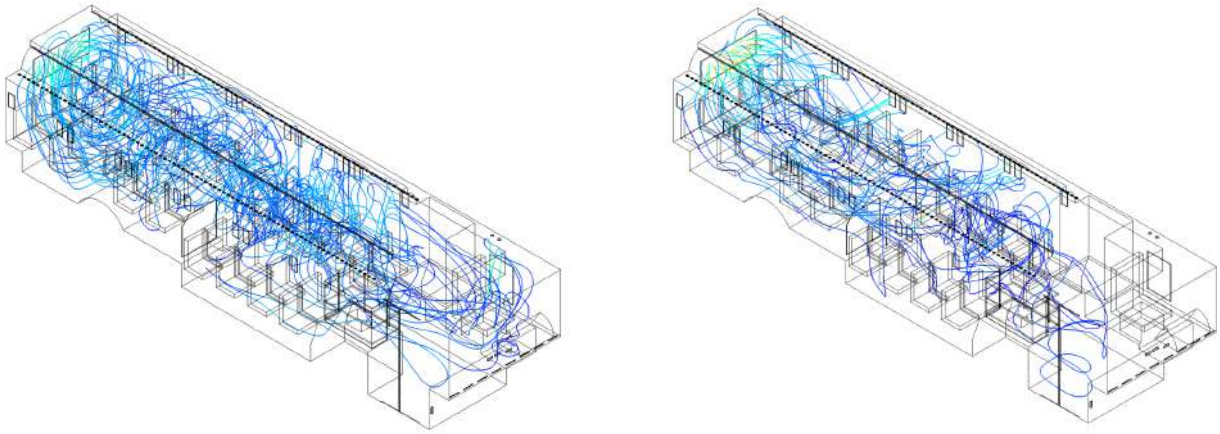
Figure 11. Comparison of Numerical Steam Distributions Traced by Water Vapor Mass Fractions Inside the Stationary (Windows Shut) and Moving (Windows Open) Bus A at Around 20 Seconds



(a) Stationary (Windows Shut) (b) Motion (Windows Open)

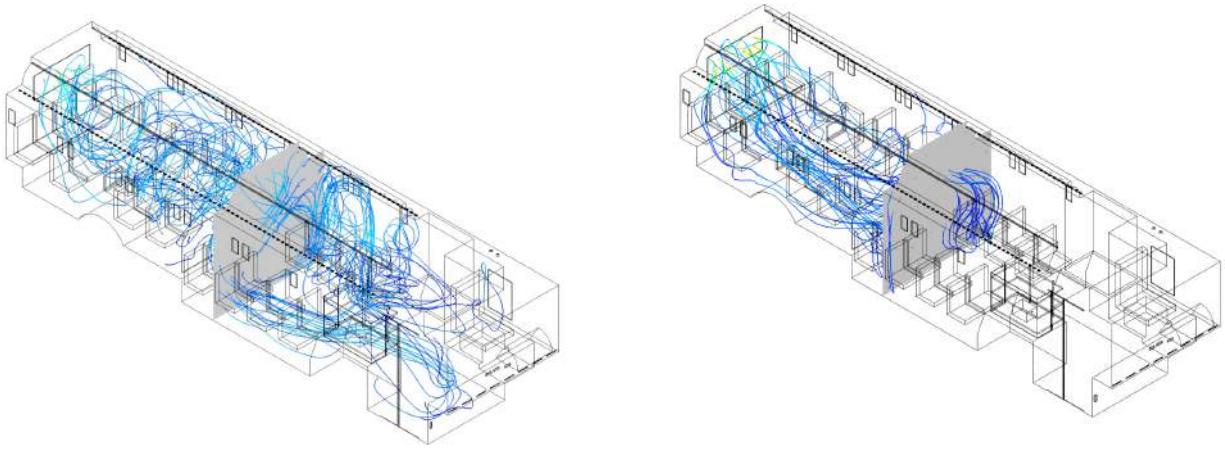
Figure 12. Comparison of Numerical Steam Distributions Traced by Water Vapor Mass Fractions Inside the Stationary (Windows Shut) and Moving (Windows Open) Bus B at Around 20 Seconds

Figure 13 compares numerical airflow and circulation patterns inside the stationary (windows shut) and moving (windows open) Bus A. It can be seen that the predicted streamlines are much less cluttered and they move faster (lighter color) when the bus is in motion than when stationary. These predicted streamlines are the possible trajectories of airborne contaminants, if released by a person and driven by the HVAC airflow in the bus cabin. Figure 14 compares the numerical airflow and circulation patterns stemming from a mid-plane inside stationary (windows shut) and moving (windows open) Bus A. Streamlines are spread throughout the stationary bus, but they only occur in the back-half region of the passenger compartment when the bus is in motion. Similar airflow behaviors can be observed in Bus B when it is stationary and in motion (Figure 15). Lastly, Figure 16 compares numerical airflow and circulation patterns stemming from different plane locations inside the stationary (windows shut) Bus B. Based on the respective plane location, the airflow was seen to move towards the return air ducts (located in the ceiling over the wheelchair positions behind the front axle close to the driver station).



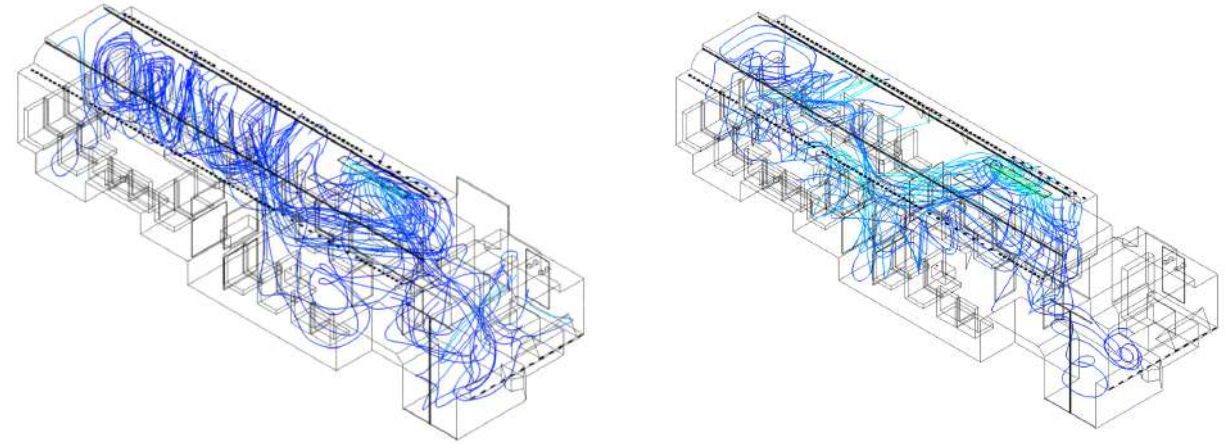
(a) Stationary (Windows Shut) (b) Motion (Windows Open)

Figure 13. Comparison of Numerical Airflow and Circulation Patterns Inside the Stationary (Windows Shut) and Moving (Windows Open) Bus A



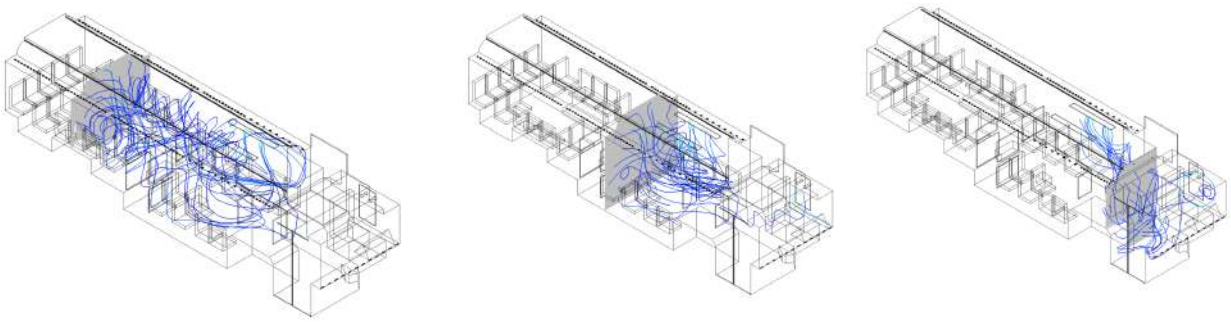
(a) Stationary (Windows Shut) (b) Motion (Windows Open)

Figure 14. Comparison of Numerical Airflow and Circulation Patterns Stemming from a Mid-Plane Inside the Stationary (Windows Shut) and Moving (Windows Open) Bus A



(a) Stationary (Windows Shut) (b) Motion (Windows Open)

Figure 15. Comparison of Numerical Airflow and Circulation Patterns Inside the Stationary (Windows Shut) and Moving (Windows Open) Bus B



(a) Back (b) Middle (c) Front

Figure 16. Comparison of Numerical Airflow and Circulation Patterns Stemming from Different Plane Locations Inside the Stationary (Windows Shut) Bus B

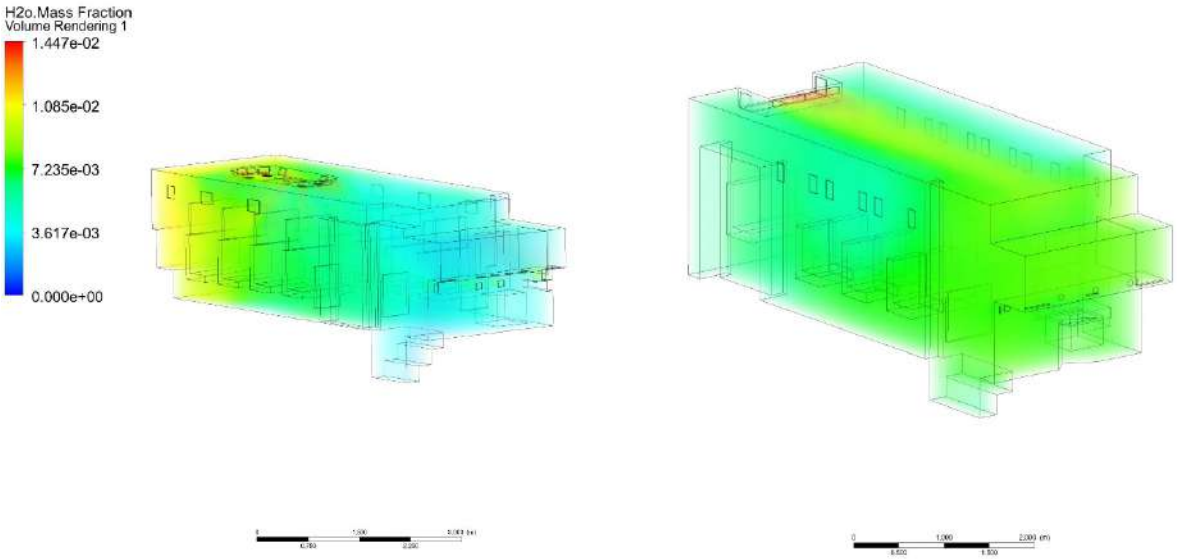
4.2.3 City Transit Bus Configurations

Two different city transit buses (C and D) with relatively similar lengths and sizes are modeled in the present study. Figure 17 compares numerical steam distributions traced by water vapor mass fractions inside the stationary Buses C and D at around 20 seconds. Both buses' return air ducts are located towards the rear of the buses. The steam propagates from the back towards the front of Bus C, whereas the steam circulates from the ceiling to the driver compartment then to the front passenger compartment and eventually travels back to the rear of the passenger compartment in Bus D. Bus C takes longer to spread the steam than Bus D. Figure 18 shows the streamline behaviors inside Buses C and D. Streamlines concentrate at the back of the passenger compartment in Bus C whereas the predicted streamlines show a significant airflow circulation in the cabin of Bus D.

4.3 Results

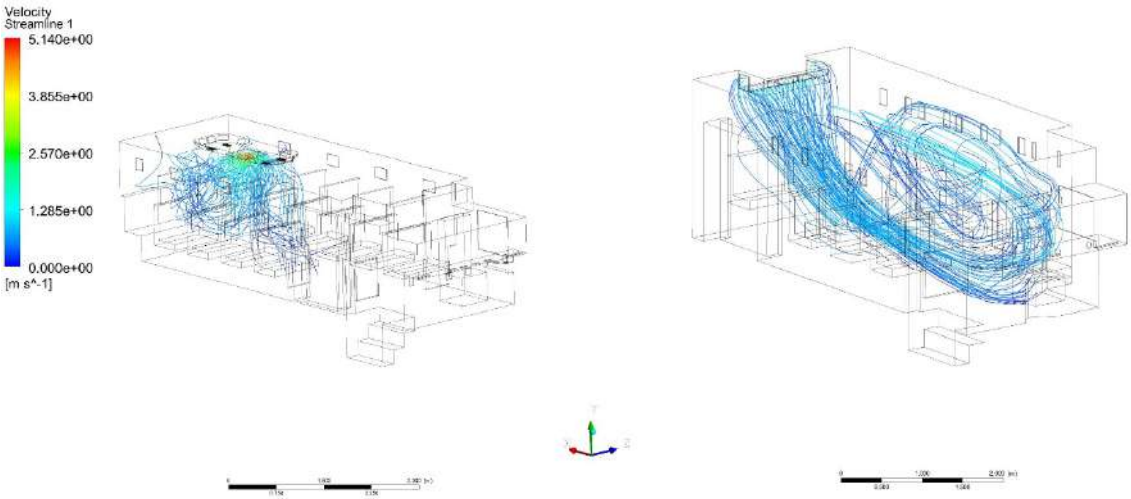
Combinations of different operation variables (e.g., vehicle stationary/in motion, windows open/shut, HVAC on/off, HVAC fresh air on/off, size of bus, configuration and parameters of HVAC system, pressure difference between inside and outside of bus, initial location of spread, size of windows, manner windows open, and many others) lead to numerous possible scenarios. In this study, given the limited time, size, and scope of the project, and the urgency for the release of results, the team focused on only some of the most impactful variables and combinations of variables.

It is important to note that the impact of the same variable could be different in different scenarios. For instance, opening the windows while stationary could have a minor impact in comparison to opening the windows while the vehicle is in motion.



(a) Bus C (b) Bus D

Figure 17. Comparison of Numerical Steam Distributions Traced by Water Vapor Mass Fractions Inside the Stationary Buses (A) Bus C and (B) Bus D at Around 20 Seconds



(a) Bus C (b) Bus D

Figure 18. Comparison of Numerical Airflow and Circulation Patterns Inside the Stationary (Windows Shut) Buses C and D

As a general observation across many scenarios (different combinations of the operation variables), the time it took for air spread was consistently a fraction of (much shorter than) the time it took to clear.

It is critically important to note that the specific time to spread and time to clear are not constants. The specific values depend on many factors, including but not limited to the details of the exact scenario (i.e. a specific combination of the above factors); however, they also depend on:

- The speed of smoke/virus introduction to the environment (for time to spread), and existing concentration of smoke/virus in the cabin (for the time to clear).

- The adopted criteria and threshold for assessing the completion of the spread or clear. For example, if the criterion was a specific particle threshold concentration value, the time values would be different than if the criterion was the ability to visually observe the smoke color or steam in the field, which is also different than if the criterion was to see the smoke color on a video recording of the experiment (which depends on the quality of video image, the distance of the recording device, lighting, and so on).

- In our experiments, we utilized the criterion of being able to visually observe the color smoke on the video recording of the experiment using the buses' security cameras (which were not of superb quality). Therefore, while the actual time values to spread and clear are not constant, the team recognizes that the truer time to spread is shorter than what we recorded and the truer time to clear is longer than what we recorded for this research. This was further evident when comparing the times recorded by the team via direct visual observation during the experiment runs against those recorded via visual observation using the recorded footage (spread values based on field visual observation were shorter than those based on visual inspection of video footage, and the opposite was true for the time to clear).

Because of the above reasons, our analyses and conclusions are more focused on the general behavior of air circulation and its impacts on different scenarios, and primarily on the relationship between time to spread and time to clear, rather than their actual time values.

With this in mind, the following discussion presents the results of the impacts of the different operation variables considered.

General Air Circulation

Air circulation within all the buses studied was efficient. As expected, the HVAC systems did the job they were designed to do, which is circulating conditioned air effectively and keeping the conditioned air longer. The size and design of the buses did not appear to have a major impact on

the circulation of air since each bus had an HVAC system specifically designed for its configuration.

Dispersion Speed

Dispersion of smoke and steam released inside the buses was very fast, with the interior of buses filling with smoke or steam within seconds (according to the adopted criteria discussed earlier)—as fast as 11 seconds based on direct visual observation in the bus.

Air Clearing Speed

The time it took to clear the interior space of the buses of smoke and steam was consistently much longer than the time it took to disperse the smoke and steam. Most cases took minutes to clear, even with fresh air and with door(s) and windows open.

Stationary versus In-Motion

The relationship between the time recorded for dispersion and clearing of the interior space on the buses was similar whether the bus was static or in motion. With windows open, the bus-in-motion cases resulted in the smoke and steam moving much faster towards the front of the bus to the driver area in comparison to when the windows were shut or when the bus was stationary. The time required to clear the air inside the bus while in motion with windows open was a little faster than when stationary; however, it was still longer than the dispersion time.

Impact of Windows

The 35-foot buses tested while in motion had different designs in terms of window openings; Bus A had small sliding windows, and Bus B had somewhat larger bottom hinged windows that opened in-ward at the top.

Initially, the team assumed that opening the windows would offer significant improvements. However, based on the results of the experiments, the team was able to identify different impacts, discussed below.

Based on our observations, opening the windows resulted in the following:

- While the vehicle was stationary, opening the windows and sometimes door(s) and plenum, in general, had a minor impact on time to spread and reduced time to clear (by possibly 50%).

- While the vehicle was in motion, opening the windows, in general:

    - Increased air turbulence inside the bus cabin.

- Increased the speeds of air circulation inside the cabin of the bus; hence reducing both the time to spread and time to clear.

- Overall, both the time to spread and time to clear were reduced. Possibly both times decreased by 30-40%. The time to spread was still much faster than the time to clear.

- Created a backward moving current parallel to the sidewalls of the bus and a constant fast-forward moving current in the middle of the bus (ending at the driver's location).

- Opening windows may have the added benefit of reducing the time to clear as well as increasing the rate of virus dilution; however:

  - It also increases the speed of virus spread.

  - Creates a forward current that is constantly targeting the driver.

  - Increases air turbulence inside the cabin that could reduce the efficiency of other virus mitigation technologies.

In general, the time of clearing was still longer than the dispersion time.

Impact of HVAC Operation

While differences were observed with respect to whether the AC was on or off, or operating under air circulation or fresh air mode, the impact on the relationship between the speed of smoke or steam dispersion throughout the cabin and the speed of clearing was not much different. In spite of slower dispersion when the AC was off and windows were shut, steam still filled the entire cabin in a manner of seconds.

Impact of Onset Location

While differences were observed depending on the location of steam release on the bus (e.g., which bus sections had a heavier concentration of steam or smoke and how fast these sections were saturated), the relationship between the speed of smoke or steam dispersion throughout the cabin and the speed of clearing was not much different. Smoke and steam filled the entire cabin in a manner of seconds and took minutes to clear. As expected, the speed of spread was faster when the onset location was closer to the HVAC return and when the HVAC was on and windows shut. As mentioned earlier, opening the windows while the vehicle was in motion increased the speed of spread (and the speed of clearing).

Impact of Emergency Hatch and Fresh Air

The 35-foot buses were tested while in motion with the rear emergency hatches open to determine if roof-mounted venting would improve the speed of clearing of smoke and steam from a bus. Opening the hatches did not have much impact on improving the speed of clearing the smoke and steam from either of the buses tested. In fact, in some cases, it created turbulence in the interior space of the passenger compartment and caused smoke and steam to travel faster to the front of the bus and the driver station.

4.4 Summary and Conclusions

In all buses and operation scenarios tested, the airborne virus released inside the passenger compartment of a transit bus spread quickly and took much longer to clear the air of virus particles, even with fresh air and with windows and doors(s) (and even plenum) open. The driver station on buses with integrated or split HVAC systems was impacted very quickly. However, the split HVAC system on a cutaway bus can be adapted to provide good protection for drivers, as explained below. It should be noted that this protects only the drivers, and does not provide any protective value for the passengers.

Before the study team arrived to do smoke and steam testing on their buses, the City of Clovis Transit had designed and installed a flexible plastic enclosure for the driver compartment on their cutaway chassis buses (with dual HVAC systems; one at the front of the bus and another at the rear) that was intended to isolate the driver from any potential virus emitted by passengers (Figure 19).

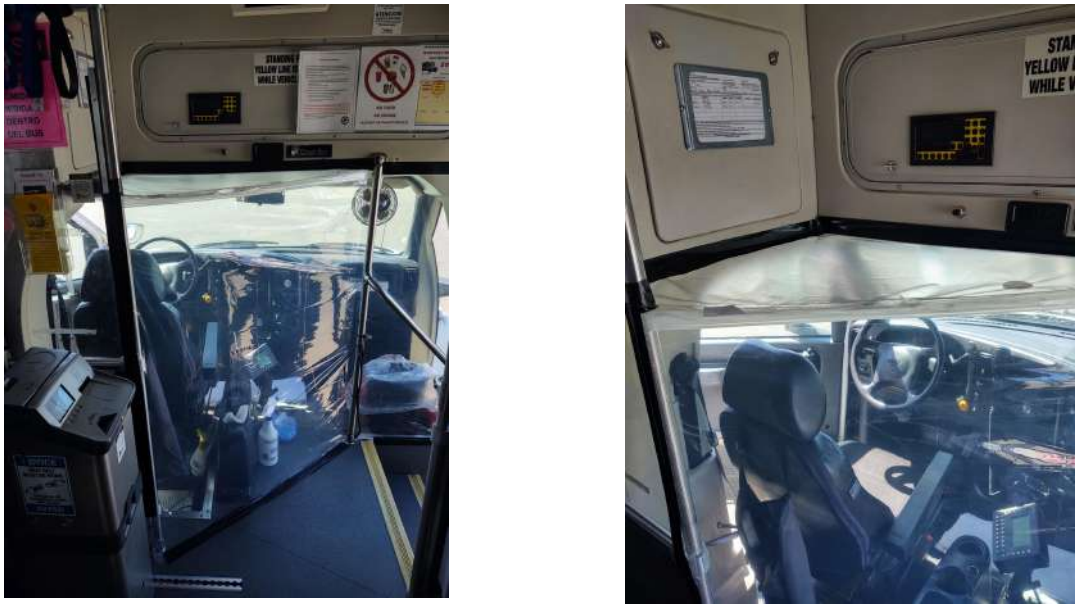


Figure 19: Two Photos Depicting the City of Clovis Transit's Flexible Plastic Enclosure to Protect the Drivers

Made from flexible, heavy-gauge polyethylene plastic and supported by simple square tubing braces, the Clovis Transit enclosures were evaluated by the study team for their effectiveness in protecting drivers from intrusion of air from the passenger area that could carry virus particles. Using the steam generator in the passenger area to fog the interior of the bus while the chassis OEM A/C system was set to bring in outside air only to the driver compartment, the team observed that the enclosure allowed the driver compartment to be pressurized by outside air so that air from the passenger area could not enter, thereby limiting the ability of airborne virus emitted by passengers to contaminate the driver compartment.

The effectiveness of the enclosure and the strategy of pressurizing the driver compartment ***only work if*** the vehicle has dual independent HVAC systems (an OEM system at the front of the vehicle and another system for the cabin), the OEM A/C system is set to bring in outside air only without recirculation, and if the enclosure sealing around the edges is maintained. The enclosures are also inexpensive to produce and install, making this a very cost-effective solution for driver protection for transit operators that use cutaway buses with dual independent HVAC systems.

Operating buses with windows open and while the vehicle is in motion reduces both the time of spread as well as the time to clear (possibly by around 30-40% each); hence, also increasing the speed of virus exposure, and reducing the total time of exposure after the removal of the viral source. Yet, the speed of spread was still much faster than the speed of clearing. However, opening the windows, also creates a fast, forward-moving current that is constantly targeting the driver. Open windows also increase air turbulence inside the cabin, which could reduce the efficiency of other virus mitigation technologies (such as those tested in the second part of this project). Accordingly, opening the windows may not offer the expected value in terms of protecting passengers or drivers from exposure once the virus is released in a bus.

Accordingly, based on these findings, the team identified potential benefits as well as possible harms from opening the windows, concluding that a safer path could be to use efficient technology (as discussed in the second part of this report) to mitigate the virus from the cabin.

Based on the above results, the study team concluded that some technology needs to be retrofitted into the current HVAC system to mitigate virus particles released inside the bus. However, such technologies would mitigate air-borne viruses only after they reach the HVAC return and would not offer protection from the virus while it travels from the infected person to the HVAC return. Accordingly, the first line of defense should be to keep a passenger or driver infected with the virus from releasing it into the bus, and this can only be accomplished today with the use of face masks properly fitted to each occupant before they enter the vehicle.

The second part of this work, "Part B) Virus Mitigation Study," presents the results of testing the effectiveness of different technologies in mitigating airborne viruses from the air as well as from settling on surfaces.

5. Part 2: Virus Mitigation Study—Devices to Effectively Eliminate Infectious Virus Particles in HVAC Systems

5.1 Introduction

The emergence of SARS-CoV-2 has changed our lives dramatically. The spread of this virus will affect the ability to congregate and travel until a safe and effective vaccine is distributed to millions of people. Until then, with the easing of different shelter-in-place policies, people will start sharing tight spaces on limited capacity public transportation modes such as transit buses, light and heavy rail, and commercial aircraft. Potential infections on such modes of transportation could be concerningly high. Since social distancing policies may not be sufficient on public transportation and wearing personal protection devices such as masks may be difficult to enforce, HVAC systems have the potential to redistribute the air and airborne virus throughout the entire cabin, risking the health of both drivers and passengers. Additionally, as a respiratory disease, SARS-CoV-2 has the potential to be spread through aerosol droplets, which can be further distributed by HVAC systems. Accordingly, Part 1 of this study aimed to understand virus circulation patterns inside the cabins of buses, and this part, Part 2, tests the impact of different approaches in mitigating potential virus circulation and infection, both within a laboratory-based HVAC system and on public transit buses.

To understand and quantify both viral circulation as well as virus mitigation inside HVAC systems, we used various devices, metrics, and experiments. To determine infectious particle circulation and mitigation, three different prokaryotic viruses—which infect bacteria and not humans—were utilized in this study: Phi6, MS2, and T7. Phi6 is a Cystoviridae lytic virus that is 85 nm in diameter and has a double-stranded RNA genome and a lipid membrane. MS2 is a Leviviridae lytic virus of 30 nm, with a positive-sense single-stranded genome with an icosahedral capsid. The T7 Podoviridae tailed lytic virus has a double-stranded DNA genome and a 55 nm icosahedral capsid, and a 30 nm long tail. The three different viruses provide size ranges and differences in structural and genome integrity that can be affected through different forms of mitigation.

Additionally, different approaches were implemented to evaluate the potential of mitigating viral spread in public transportation modes. These include heating, positive pressure environment inside the cabin, HEPA filters, concentrated UVC exposure with charged carbon filters in the HVAC systems, center point photocatalytic oxidation technology, and UVC light. Moreover, these experiments were conducted on different vehicles with distinct HVAC sizes and configurations, as well as in a laboratory HVAC system setting. Results of this study could be significantly valuable and directly lead to improved protection of passengers and drivers on public transportation modes against all forms of airborne viruses, both locally as well as across the entire globe.

5.2 Materials and Methods

Biologicals

The bacteriophages used in this study were Phi6 (DSMZ, Braunschweig, Germany), MS2 (ATCC, Chicago, IL), and T7 (ATCC, Chicago, IL). Phi6 was cultured with its bacterial host Pseudomonas spp. Her1102 (DSMZ, Braunschweig, Germany), MS2 was cultured with its bacterial host Escherichia coli C3000 (ATCC, Chicago, IL), and T7 was cultured with its bacterial host Escherichia coli B (ATCC, Chicago, IL). Bacteriophages were cultured to a stock concentration of at least 1010 PFU/mL and distributed through aerosol in experiments at a concentration of at least 109 PFU/mL. Stock concentrations of bacteriophage and sprayed dilutions of bacteriophage were made in Saline Magnesium (SM) buffer (100 mM NaCl, 8 mM MgSO4•7H2O, 50 mM Tris-HCl, pH 7.5 in dH2O).

Laboratory HVAC Experiments

47 mm diameter 0.02 μm pore size Anodisc Circle with support ring filters (Whatman) were placed within 47 mm open-face plastic filter holders (F&J Specialty Products, Inc., Ocala, FL) and placed at the intake and output of the laboratory HVAC system (Figure 20. Devices Utilized to Measure Bacteriophages in the Air in both Laboratory and Bus Experiments). 15 mL of each bacteriophage in SM buffer was sprayed into the intake of the HVAC system while the system was running. After 5 minuets, with the HVAC system running, the filter holders were removed from their positions, and placed in 5 mL SM buffer. The filters in buffer were stored on ice (4˚C) until use in the laboratory.

Bus Experiments

47 mm open-face filter holders with 0.02 μm pore size filters were set at 6 different locations throughout the bus, one at each intake and 4-5 at different outputs depending on the bus (Figure 1). Additionally, 4 swab sites of equal area to that of the filters were designated for surface virus collection to determine viral settling (Whatman OmniSwab). 15 mL of each bacteriophage diluted in SM buffer was sprayed into the intake of each bus while the HVAC system was running. After 5 minuets, with the HVAC system running, the filter holders were removed from their positions, and placed in 5 mL SM buffer. Surface swabs at the designated swab sites were swabbed 10x and the swab head was ejected into 5 mL SM buffer. The filters and the swabs in buffer were stored on ice (4˚C) until use in the laboratory.

Anodisc Circle with support ring filters (Whatman)

47 mm open-face plastic filter holders

Figure 20. Devices Utilized to Measure Bacteriophages in the Air in both Laboratory and Bus Experiments

Laboratory Infectious Bacteriophage Determination

Once at the laboratory, the filters and swabs in solution were inverted and rotated (Rotavamp, 20 rev/min) for 1 hour at room temperature to promote bacteriophage dissipation into solution. Samples were then centrifuged at 7,000 rpm for 5 minutes. Double layer plaque assays were then performed on the host bacteria for each bacteriophage to determine the number of infectious virions, as measured by plaque-forming units per mL (PFU/mL).

Treatment Conditions

Properties of the treatment devices are listed below:

- Photocatalytic oxidation inserts: max 2353 CFM, 110V / 60 hz Lamp 36-watt, 24 inch, titanium dioxide media.
- Photocatalytic oxidation filter: 36”X18” X 6”, lamp 3 X 31”, 80-watt, titanium dioxide media.
- Stand Alone UVC Lamp: 12”, 18 watt, plus 12”X12” X 1” activated carbon filter Merv 7, @ 90.0% efficiency
- HEPA filter Merv-17: 12”X 12”X 4” @99.97% efficiency
- HEPA filter Merv-19: 12”X 24”X11.5” @99.995% efficiency

Laboratory HVAC experiments were conducted at cooling conditions (57˚F, 13.9˚C, 75% Relative Humidity), heating conditions (130˚F, 54.4˚C, 28% RH), HEPA filter (MERV-17, 57˚F, 13.9˚C, 73% RH), HEPA filter (MERV-19, 57˚F, 13.9˚C, 73% RH), carbon filter (MERV-7, 57˚F,

13.9˚C, 73% RH), carbon filter with UVC light (MERV-7, 24 W, 57˚F, 13.9˚C, 73% RH), photocatalytic filter panel with UVC (24 W, 57˚F, 13.9˚C, 75% RH), and photocatalytic oxidative insert (24 W, 57˚F, 13.9˚C, 72% RH).

Bus "A" experiments were conducted under cooling conditions (73˚F, 22.8˚C), heating conditions (83˚F, 28.3˚C), HEPA filter (MERV-19, 73˚F, 22.8˚C), photocatalytic filter panel with UVC (24 W, 73˚F, 22.8˚C), photocatalytic oxidative insert (24 W, 73˚F, 22.8˚C), UVC light (24 W, 73˚F, 22.8˚C) and positive air pressure (0.5-inch wc, 73˚F, 22.8˚C).

Bus "B" experiments were conducted at cooling (73˚F, 22.8˚C) and heating (103˚F, 39.4˚C) temperature conditions.

5.3 Results

Heating and UVC light effectively eliminate infectious viruses in a laboratory HVAC system

Filters were positioned at the intake and output of the laboratory HVAC system, while different modes of mitigation were placed at the intake. 15 mL of each virus were sprayed into the system, where the number of infectious viruses could be determined prior to treatment at the input and after treatment at the output. Normal cooling conditions were tested, followed by two different heating conditions (86˚F and 130˚F), two different HEPA filters (MERV-17 and MERV-19), two different photocatalytic devices (filter and insert), and carbon filters in the absence or presence of UVC light (Figure 21).

The large RNA virus Phi6 was effectively eliminated in all cases using heating and UVC light. Heating at 86˚F mitigated 92.8% of the infectious viral input (Figure 21A, light orange bar), while 130˚F mitigated 98.9% (Figure 21A, dark orange bar). HEPA filters worked about as well as heating at 86˚F, 90.5% for the MERV-17 filter (Figure 21A, light grey bar), and 93.0% for the MERV-19 filter (Figure 21A, dark grey bar). The photocatalytic filter and insert, each with UVC light, mitigated the infectivity of Phi6 well: 99.4% (Figure 21A, light yellow bar) and 99.9% (Figure 21A, dark yellow bar), respectively. The carbon filter without UVC light was not very effective at mitigating infectious Phi6 (57.1%, Figure 21A, light green bar); however, when UVC light was added, the effectiveness rose dramatically (98.9%, Figure 21A, dark green bar). Running the laboratory HVAC system at normal cooling conditions (57˚F, Figure 21A, blue bar) caused a 50.6% reduction in infectious Phi6 virus.

The smaller RNA virus MS2 was effectively mitigated in high heat conditions (130˚F, 98.3%, Figure 21A, dark orange bar), with the photocatalytic insert with UVC light (97.8%, Figure 21A, dark yellow bar), and with UVC light in combination with the carbon filter (98.2%, Figure 21A, dark green bar). HEPA filtration (MERV-17, 51.0%, Figure 21A, light grey bar) and the photocatalytic filter with UVC light (86.9%, Figure 21A, light yellow bar) did not mitigate this smaller RNA virus as robustly as the larger RNA virus. Normal cooling conditions (26.6%, Figure

21A, blue bar) and carbon filtration without UVC light (71.1%, Figure 21A, light green bar) also had differing effects on this small virus. The effects of heating at 86˚F and filtration with a MERV-19 HEPA filter were not determined with this virus in the laboratory setting (Figure 21A, n.d.).

Heating and treating with a photocatalytic insert with UVC light each effectively mitigated the infectivity of the large DNA virus T7, 95.3% (Figure 21A, dark orange bar) and 98.1% (Figure 21A, dark yellow bar), respectively. The other UVC light treatments, with the photocatalytic filter (86.4%, Figure 21A, light yellow bar) and with the carbon filter (86.7%, Figure 21A, dark green bar) were each effective, though not as effective against the RNA viruses. HEPA filtration (MERV-17, 63.3%, Figure 21A, light grey bar) was similarly effective to carbon filtration (67.2%, Figure 21A, light green bar). Running the T7 virus through the laboratory HVAC system under cooling conditions yielded results similar to the large RNA virus (53.3%, Figure 21A, blue bar). As with the MS2 virus, the effects of heating at 86˚F and with a MERV-19 HEPA filter were not determined for the T7 virus under laboratory conditions (Figure 21A, n.d.).

The total viral mitigation of all three viruses showed that heating and UVC-treatment had a profound effect on viral spread throughout the laboratory HVAC system (Figure 21B). Normal heating conditions (86˚F, 93%, Figure 21B, light orange bar) and high heat conditions (130˚F, 98%, Figure 21B, dark orange bar) were both effective at eliminating infectious virus. UVC treatments were also effective at eliminating the virus, as the photocatalytic filter with UVC (91%, Figure 21B, light yellow bar), the photocatalytic insert with UVC (99%, Figure 21B, dark yellow bar), and the carbon filter with UVC light (95%, Figure 21B, dark green bar) all determined. Only the MERV-19 HEPA form of filtration showed effective mitigation of the viruses (93%, Figure 21B, dark grey bar), while MERV-17 HEPA (68%, Figure 21B, light grey bar) and carbon filtration (65%, Figure 21B, light green bar) were not very effective at eliminating the infectious virus. Simply running the laboratory HVAC system under normal cooling conditions only eliminated 44% of the infectious viruses (Figure 21B, blue bar).

A., Sprayed Phi6 (left columns), MS2 (middle columns), and T7 (right columns), were collected via filter after running through HVAC system under conditions listed in the legend and in the Materials and Methods section. Data are presented as percent of infectious virus that has been mitigated by each condition at the output of the HVAC system as compared to the amount of input to the HVAC system. N.D. denotes not determined. B., Combined results from the three viruses according to the treatment condition.

Figure 21. Heating and UVC Light Effectively Eliminate Viruses in a Laboratory HVAC System

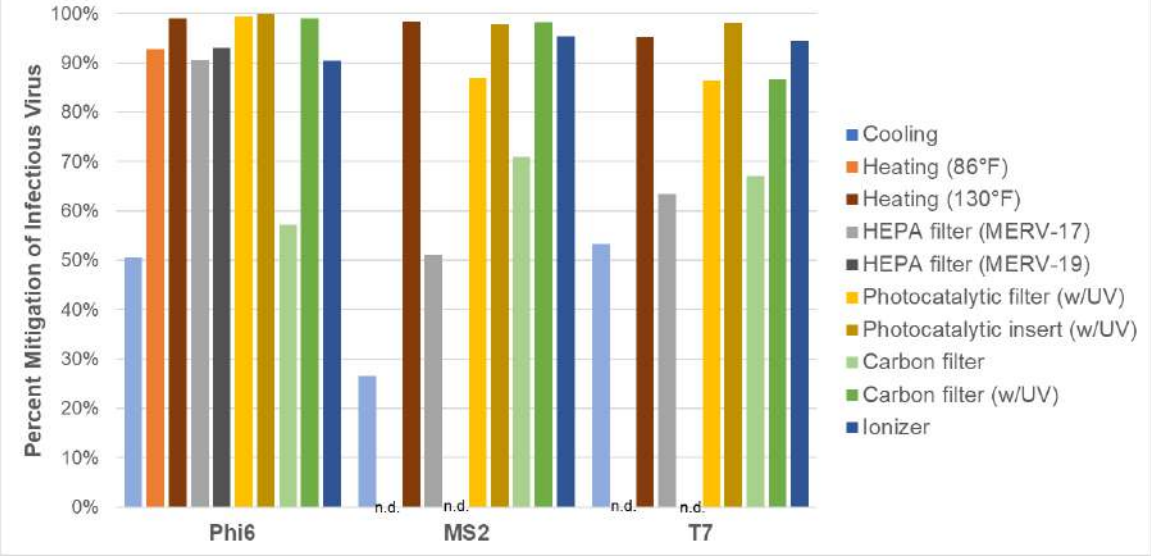


Figure 21A: Specific Viral Mitigation Laboratory HVAC System

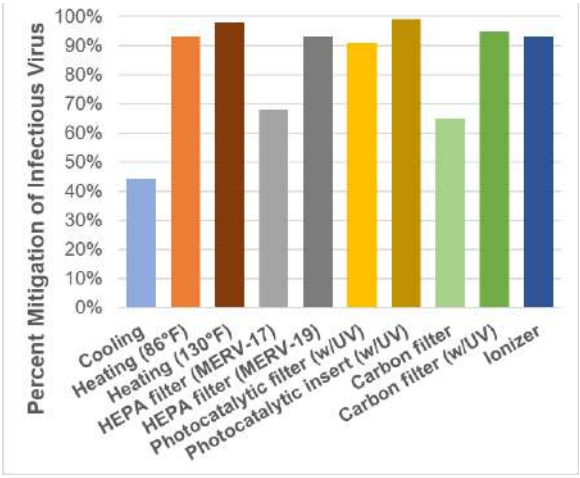


Figure 21B: Total Viral Mitigation Laboratory HVAC System

UVC light effectively eliminates infectious viruses in buses

Bus "A" was fitted at the HVAC intake with identical devices, as used in the laboratory experiments. A photocatalytic filter, a photocatalytic insert, and UVC light all effectively eliminated viral spread collectively at the bus outputs sampled (Figure 22A). The photocatalytic filter mitigated 100% of Phi6, 97.3% of MS2, and 100% of T7 (Figure 22A, light yellow bar). The photocatalytic insert mitigated 100% of Phi6, 99.3% of MS2, and 100% of T7 (Figure 22A, dark yellow bar). UVC light mitigated 100% of Phi6, 98.9% of MS2, and 100% of T7 (Figure 22A, dark green bar). HEPA (MERV-19) filtration effectively eliminated viruses as well, though not as well as UVC light (Phi6 98.3%, MS2 98.4%, and T7 97.2%, Figure 22A, dark grey bar). Creating positive air pressure (0.5 inches water column) in the bus resulted in mitigation of the viruses (Phi6 97.4%, MS2 86.6%, and T7 94.6%, Figure 22A, black bar), though the results were not as robust as with UVC or HEPA treatments. Running the bus HVAC system under high heating conditions improved mitigation of the spread of the infectious virus as compared with running the bus HVAC system under cooling conditions (Heating: Phi6 95.7%, MS2 90.8%, T7 95.7%, Figure 22A, orange bar; Cooling: Phi6 83.1%, MS2 85.8%, T7 83.1%, Figure 22A, blue bar).

Bus "B" was sampled only under cooling and heating conditions; no further treatments were conducted. Under cooling conditions, there was substantial loss or mitigation of the large viruses within the bus HVAC system (Figure 22B, blue bars). Phi6 was mitigated 91.7%, while T7 was mitigated 97.1%. The smaller virus, MS2, was mitigated similar to that observed in Bus "A" (71.0%). Heating within the HVAC system of Bus "B" resulted in an increase of mitigation of the RNA viruses (Figure 22B, dark orange bars) Phi6 (97.6%) and MS2 (94.1%). Paradoxically, heating within the HVAC system of Bus "B" also caused a reduction in the mitigation of the DNA virus T7 (91.9%) compared to cooling conditions.

The combined mitigation of the infectious viruses on the buses was most affected by treatments using UVC light (Figure 22C). The photocatalytic filter with UVC (99%, Figure 22C, light yellow bar), the photocatalytic insert with UVC (100%, Figure 22C, dark yellow bar), and the carbon filter with UVC (100%, Figure 22C, dark green bar) were the most effective treatments. HEPA filtration (MERV-19, 98%, Figure 22C, dark grey bar) was also quite effective. HVAC heating conditions (83˚F, 92%, Figure 22C, light orange bar; 103˚F, 95%, Figure 22C, dark orange bar) were the next most effective means of mitigating viruses on the buses. Positive pressure (93%, Fig. 2C, black bar) and normal HVAC cooling conditions (86%, Figure 22C, blue bar) had a degree of effectiveness as well.

Large viruses settling on bus surfaces were effectively eliminated by treatment conditions

The previous experiments were all measured by placing a filter at specific intakes and outputs within each of the buses. While it is important to understand how much infectious virus is transmitted in each bus, it is also important to understand how much infectious virus can settle on surfaces. Therefore, we swabbed at four different locations throughout the bus after spraying each

virus under each condition tested for filtering. The results are presented as a percentage of each virus detected as compared to the cooling condition.

A., Sprayed Phi6 (left columns), MS2 (middle columns), and T7 (right columns), were collected via filter after running through the bus "A" HVAC system under conditions listed in the legend and in the Materials and Methods section. Data are presented as percent of infectious virus mitigated by each condition from the collective output of the HVAC system as compared to the amount of input to the HVAC system. B., Sprayed Phi6 (left columns), MS2 (middle columns), and T7 (right columns), were collected via filter after running through the bus "B" HVAC system under cooling and heating conditions. C., Combined results of the elimination of the three viruses from both of the buses.

Figure 22. UVC light effectively eliminated infectious virus on buses.

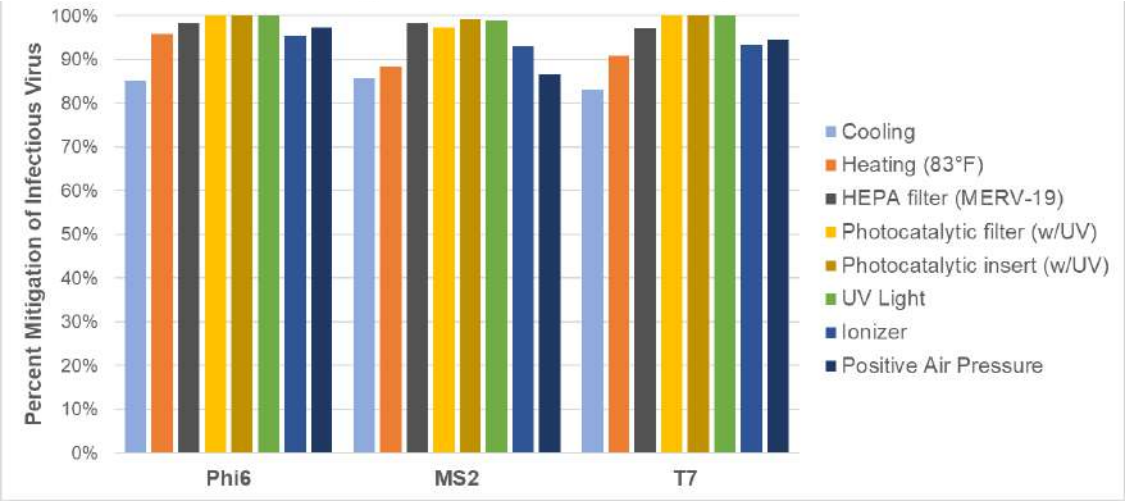


Figure 22A: Specific Mitigation of Viruses on Bus "A"

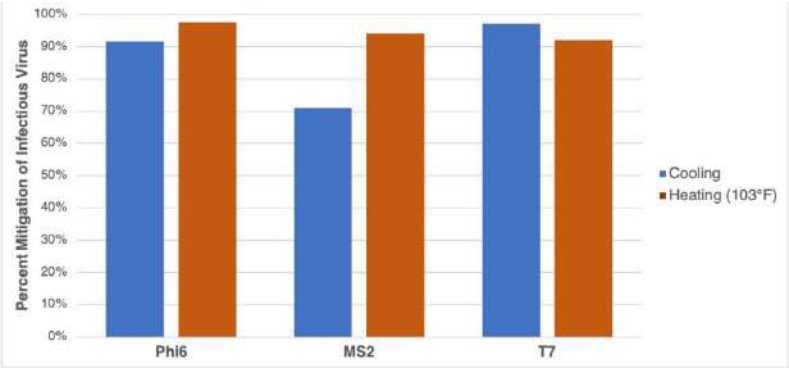


Figure 22B: Specific Mitigation of Viruses on Bus "B"

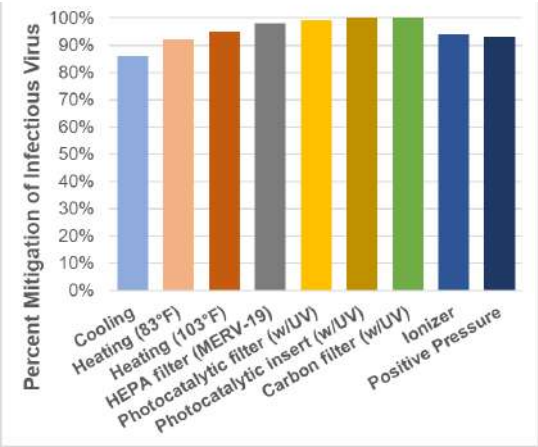


Figure 22C: Total Mitigation of Viral Output on Buses

The large RNA virus, Phi6, was effectively not detected on bus surfaces for every treatment condition tested. With the exception of low heat conditions used in Bus "A", 90% of the virus was not found compared to cooling conditions. In all other treatments, 100% of the virus was not found compared to the cooling conditions in Bus "A" and Bus "B" (Figure 23A, heating 103˚F, Phi6, dark orange bar).

The large DNA virus, T7, displayed similar results to the large RNA virus, with no detection of virus on surfaces under heating conditions in Bus "B" (Figure 23A, heating 103˚F, T7, dark orange bar) and under positive pressure conditions in Bus "A" (Figure 23A, T7, black bar). HEPA filtration also prevented viral settling in Bus "A" (Figure 23A, T7, 99%, dark grey bar), while the photocatalytic filter (Figure 23A, T7, 95%, light yellow bar) and photocatalytic insert (Figure 23A, T7, 96%, dark yellow bar) each had a positive effect on viral settling compared to cooling conditions. Heating in Bus "A" affected viral settling on surfaces somewhat (Figure 23A, heating 83˚F, T7, 87%, light orange bar), as did use of UVC light (Figure 23A, T7, 87%, dark green bar).

The small RNA virus, MS2, displayed more variable effects with respect to settling on surfaces. While heating at 103˚F in Bus "B" (Figure 23A, MS2, dark orange bar), use of a HEPA filter (Figure 23A, MS2, dark grey bar) and positive air pressure in Bus "A" (Figure 23A, MS2, black bar) each resulted in no detection of settled MS2 virus, use of the photocatalytic filter or use of UVC light resulted in no change in settling compared to cooling treatments. Heating at 83˚F in Bus "A" resulted in a 23% decrease in detection rate compared to cooling conditions (Figure 23A, MS2, light orange bar), while the photocatalytic insert caused a 68% decrease in detection rate compared to cooling conditions (Figure 23A, MS2, dark yellow bar).

The combined prevention of viral surface settling was most effective with high heat (103˚F, Figure 23B, dark orange bar), HEPA filtration (MERV-19, Figure 23B, dark grey bar), and positive pressure in the bus (Figure 23B, black bar). In addition to effectively killing infectious virus, UVC light treatments also helped to prevent viral settling (Figure 23B, photocatalytic filter with UVC, light yellow bar; photocatalytic insert with UVC, dark yellow bar; UVC light, dark green bar).

Low heating conditions were as effective as the catalytic filter, while normal cooling conditions on the buses had little effect on viral surface settling.

A., Sprayed Phi6 (left columns), MS2 (middle columns), and T7 (right columns), were collected via swab at designated spots after running through the bus "A" HVAC system under conditions listed in the legend and in the Materials and Methods section. Data are presented as percent of infectious virus mitigated by each condition from the collective swabs as compared to the amount of input to the HVAC system. Swabs from heating conditions at 103˚F were collected from bus "B", while the rest of the conditions in the figure and legend were swabs collected from bus "A". B., Combined results on the settling of the three viruses according to treatment condition.

Figure 23. Larger Viruses Were More Efficiently Mitigated by Treatment Conditions And Did Not Settle on Bus Surface Areas.

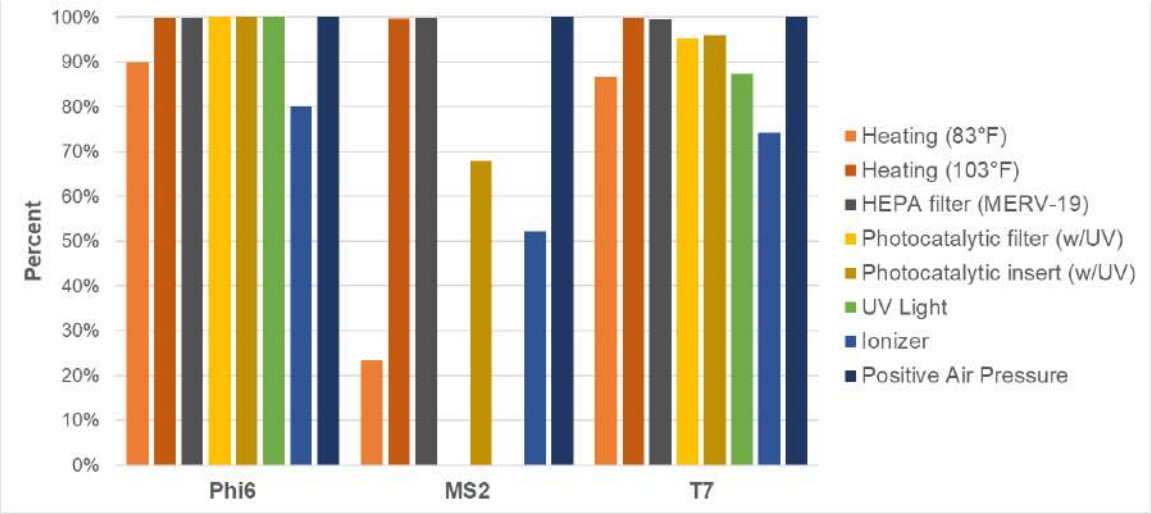


Figure 23A: Specific Mitigation of Viral Settling in Buses

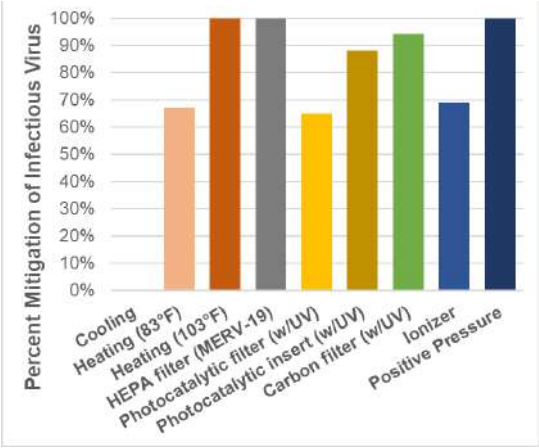


Figure 23B: Total Mitigation of Viral Settling in Buses

Overall effectiveness of treatments on infectious viruses

Figure 24 shows the collective effectiveness of each of the treatment conditions for all of the viruses. Cooling conditions were able to eliminate 73% of the viruses from all the experiments conducted. Heating conditions progressively became more effective at eliminating the viruses in a gradient-dependent manner. Medical-grade HEPA filtration was equally as effective as high heat conditions, though intermediate HEPA filtration was not any more effective than carbon filtration, and each was about as effective as normal cooling HVAC conditions. Positive pressure was also effective at preventing viral spread and subsequent viral infection. UVC light treatments were all effective at eliminating infectious viral particles in the experiments. From these collective experiments, we ranked all of the treatments according to their effectiveness in eliminating infectious virus (Table 1). From this, it was determined that the photocatalytic insert with UVC light was the most effective treatment to mitigate viruses.

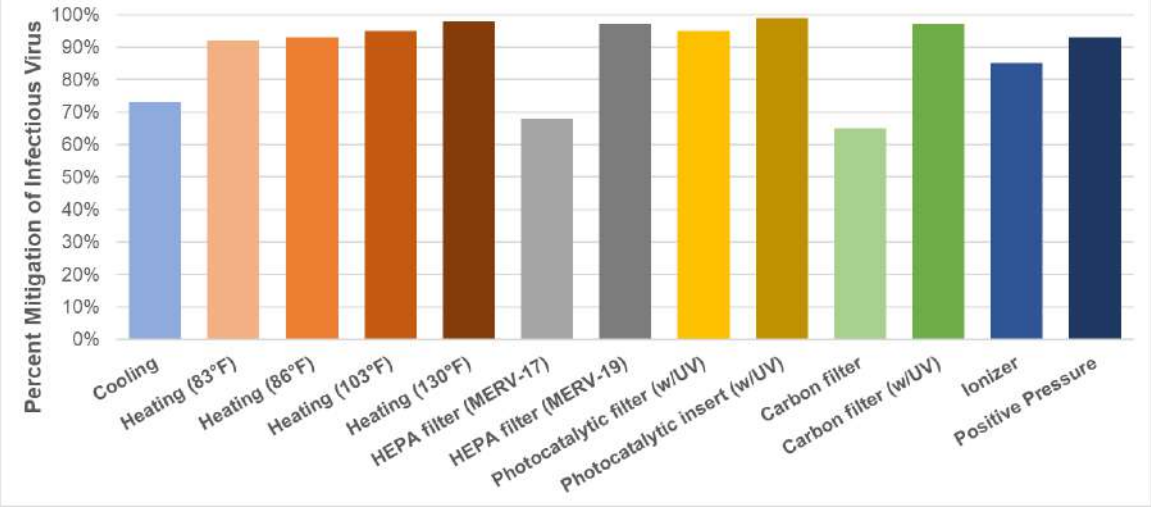


Figure 24. Combined Viral Mitigation from All Experiments Determine that Heating and UVC Light Treatment are Most Effective

The effectiveness of eliminating infectious viruses was combined from all the experiments. Data are presented as percent of infectious virus mitigated by each condition from the collective output from the laboratory and field experiments.

Table 1. Ranking of Testing Viral Mitigation Technologies

Treatment	Total Mitigation Rank	Lab Mitigation Rank	Field Mitigation Rank
Cooling	11	10	9
Heating (83˚F)	9	-	8
Heating (86˚F)	8	5	-
Heating (103˚F)	6	-	5
Heating (130˚F)	2	2	-
HEPA filter (MERV-17)	12	8	-
HEPA filter (MERV-19)	4	4	4
Photocatalytic filter (w/UVC)	5	7	3
Photocatalytic insert (w/UVC)	1	1	1
Carbon filter	13	9	-
Carbon filter (w/UVC)	3	3	2
Ionizer	10	6	6
Positive Pressure	7	-	7

5.4 Summary and Conclusions

The purpose of this part, Part 2 of this study, was to test the effectiveness of different devices in mitigating live airborne viruses. This differs from other studies which use only inert particle sizes to determine the effectiveness of treatments. The tests included evaluations within a laboratory HVAC system and two different styles of buses. The tests determined the infectivity of three

different viruses at input to the HVAC system and at various outputs, and in settling on bus surfaces. Three different, live, bacteriophage viruses were tested and evaluated according to their size, structure, and genome composition.

Collectively, from these experiments, some key observations can be made. Consistently, from the laboratory to the field, the most efficient devices for the mitigation of live viruses were the photocatalytic inserts, heating at very high temperatures, UVC lights, MERV-19 HEPA filters, and photocatalytic filters, in this order. The viruses tested were spread by aerosol, much as respiratory viruses would be. Heating would help to quickly dry the aerosol particles and prevent spreading. High-efficiency filtering would also prevent the spread of large aerosol particles. Importantly, devices containing UVC light exposure were very effective at directly eliminating viruses, even during a short period of treatment.

We observed differences in viral mitigation between the laboratory HVAC system and the bus HVAC systems in the field. This can be explained by the settling of viral particles on the surfaces within the HVAC system, where the surface area and the travel distance are much greater in the bus than in the lab. Further, differences in airspeed can result in more spread but less settling of virus. Each HVAC system has a difference in airspeed that therefore affects viral spread. Creating positive pressure within the bus confirms this observation, as there was an increase in viral spread, yet no viral settling.

Surprisingly, a large percentage of airborne virus mitigation occurs without treatment in buses. Simply running the bus HVAC system under normal cooling conditions mitigated up to 85% of the viruses. However, it should be noted that this would leave at least 15% of the viruses live and potentially infectious. If a single sneeze or cough contains millions of viruses, this would still allow hundreds of thousands of viruses to spread throughout an HVAC system with the potential to infect. With that said, simply heating the HVAC system was effective at eliminating infectious viruses, presumably through drying out the aerosol particles to which the viruses can attach. The gradient created by increased temperatures affecting viral infectivity across the various experiments supports this observation. This is an important finding for transit agencies and riders, given that winter seasons are notorious for colds and virus infection and riders typically fear potential infection from public transportation.

While these experiments were originally designed to determine the effectiveness of various devices to prevent the spread of SARS-CoV-2, the use of three different viruses of various sizes, structures, and genome integrity allows the observations to be applied to many different viruses. Small viruses such as MS2 are much more difficult to mitigate in an HVAC system than large viruses, although their potential for surface settling is less. The tested virus most similar to SARS-CoV-2, Phi6, was most affected by the photocatalytic inserts and filters both in the lab and in the field. This virus was also affected greatly by UVC light treatment and medical-grade HEPA filtration, and creating positive pressure helped to prevent this large virus from settling on surfaces.

To conclude, the experiments conducted are of critical importance with respect to determining how infectious viruses spread within an HVAC system in a lab (which can be applied to all HVAC systems) and within HVAC systems on buses. These experiments are unlike any other to date, where other experiments typically examine particle movement (which would not convey the effectiveness of possible virus-killing mechanisms such as the use of UVC light-containing devices). These data can be interpreted to determine which treatments are effective at eliminating large RNA viruses such as SARS-CoV-2 and other viruses of varying sizes and genomes. Therefore, the use of photocatalytic inserts, filters, and UVC light can be recommended as effective treatments in mitigating airborne viruses that can be spread by HVAC systems. High-temperature heating can also be effective. Further, medical-grade HEPA filtration and creating a positive pressure environment, while not as effective as the other treatments at eliminating infectious virus, are suggested to prevent viral settling on surfaces. These data should provide conclusive evidence for mitigating viral spread, settling, and infectivity in any HVAC system.

6. Post-Project Air Quality Exploratory Measurements

Upon the completion of the project and release of preliminary findings, the team received feedback about concerns of potential air quality hazards from the use of photocatalytic oxidation and UVC technologies. Specifically, there were concerns about possible toxic by-products from these two technologies (photocatalytic oxidation and UVC lights).

While the project experiments had already concluded and project funding was depleted, the team was concerned about releasing findings that may be potentially hazardous to the public. Accordingly, the team pursued additional funding and delayed the release of this report. The team succeeded in securing some additional funding that allowed for the procurement of three air quality measurement devices and for running a few exploratory experiments in the field. The procured devices were selected to measure concentrations of formaldehydes, ozone, and volatile organic compounds (VOCs) in the vehicles (Figure 25).

The team conducted two groups of measurements on busses in the field, one with the bus being stationary and one with the bus in motion on the freeway. Both groups of experiments were conducted without the bacteriophage viruses. Each group of experiments included four runs: a baseline run without any virus mitigation devices installed in the bus HVAC system, and three runs with virus mitigation devices installed in the bus HVAC system—one run with the photocatalytic oxidation inserts, one with the photocatalytic oxidation filter, and one with the UVC lights. Measurements in each run were recorded for 5 minutes.

Recorded measurements of these runs are presented in Table 2. The results indicate no differences in values between the control runs that included no virus mitigation devices and the other runs with these technologies retrofitted within the bus HVAC system. Additionally, as may be expected given the existence of traffic on the freeway, the results indicate a slight increase in the recorded ozone concentration on the freeway in comparison to when the bus was stationary in the maintenance yard.

Formaldehyde Meter HFX205

Gas Detector AQ-200 Set EOZ
with sensor head (Ozone 0-10 ppm)

Gas-Pro pumped PID (VOCs)

Figure 25. Three Air Quality Measurement Instruments Used by the Team

Table 1. Air Quality Measurements in the Exploratory Runs

Run Group	Virus Mitigation	VOCs (ppm)	Formaldehyde (ppm)	Ozone (ppm)
Vehicle Stationary	None	0	0.00	0.11
	PCO Inserts	0	0.00	0.11
	PCO Filter	0	0.00	0.11
	UVC Light	0	0.00	0.11
Vehicle In-Motion	None	0	0.00	0.12
	PCO Inserts	0	0.00	0.12
	PCO Filter	0	0.00	0.12
	UVC Light	0	0.00	0.12

7. Final Summary, Conclusions, and Further Work

With the onslaught of the novel coronavirus and the COVID-19 pandemic, transit operations suffered significant reductions in ridership due to fear of infection. Accordingly, our team performed an exploratory, fast-paced study with two objectives: (1) to assess the potential risk of viral spread in transit buses via understanding and modeling air circulation in transit vehicles under different conditions of operation, and (2) to try to identify effective, cost-efficient technologies that could be utilized to mitigate live viruses from the cabins (air and surfaces) of transit buses.

Part 1: Airflow Study

For the first objective, the team conducted different experiments on several buses (with different characteristics (e.g., size, interior arrangement, HVAC arrangements and characteristics, etc.) and under different combinations of operation conditions (e.g., stationary and in-motion, with windows or doors open and shut, with HVAC on and off, with HVAC fresh air on and off, with the emergency hatch open and shut, and with the source of viral spread at different locations in the vehicle).

The team adopted three approaches to capture air circulation inside the vehicles: (1) modeled air circulation via anemometer measurements at various locations and heights, and (2) visualized and recorded air circulation using non-toxic colored smoke, and (3) visualized and recorded air circulation using white steam. Measurements from these different approaches were further integrated to build CFD models for the different buses using the ANSYS software.

The team was primarily interested in capturing the relationships between the speed by which the virus would spread throughout the bus cabins and the speed needed to clear the cabin of the virus. The team measured these two variables under different cases of operations and different combinations of cases.

It is important to note that the absolute values of these measurements are not constant. The absolute values depend on a multitude of factors (e.g., the speed of introduction of the virus, the adopted thresholds to indicate full spread or full clearing of the virus, the size of the cabins, properties of the HVAC system, and specific conditions of operations, among others). Accordingly, the team was more focused on the relationships between these two variables rather than exact values.

Operating the buses with windows open and while the vehicle is in motion reduces both the time of spread as well as time to clear (possibly by around 30-40% each); hence, increasing the speed of virus exposure and reducing the total time of exposure after the removal of the viral source. Yet, the speed of spread was still much faster than the speed of clearing. However, opening windows also creates a fast, forward-moving current that is constantly targeting the driver. It also increases air turbulence inside the cabin, which could reduce the efficiency of other virus mitigation

technologies (such as those tested in the second part of this project). Thus, opening the windows may not offer the expected value in terms of protecting passengers or drivers from exposure once a virus is released.

Based on these findings, the team identified potential benefits as well as possible harms from opening the windows, concluding that the safer path could be to focus on using technology to mitigate the virus from the cabin.

The team encourages the introduction of fresh air into the cabin. Per our virus mitigation technologies test results, positive pressure (which effectively means bringing in more air into the bus) mitigated larger percentages of virus from the air and prevented viruses from settling on surfaces. However, opening the windows may not be the best way to do so, mainly because (as discussed earlier) doing so speeds up the virus circulation within the bus cabin, adds turbulence, and creates a continuous forward-moving airflow (inside the cabin) targeting the bus driver.

The team has not conducted experiments to specifically investigate the impacts of viral load dilution from opening the windows. However, besides the potential of viral dilution, the team also suspects a potential for viral load redistribution that (given the constant fast-forward current) could possibly increase the viral load in the driver area.

The salient finding for this objective indicated the fast speed of viral spread and slower speed of virus clearing, almost consistently across all investigated operation conditions. This finding is in line with the objectives and expectations of HVAC system designs since they are designed to efficiently circulate as well as maintain the air-conditioned air across the vehicle. Unfortunately, though, this efficiency is not favorable for limiting viral spread or clearing in transit buses.

Based on these results, the study team concluded that some technology needs to be retrofitted into current HVAC systems to mitigate any virus particles released inside the bus. However, such technologies would mitigate airborne viruses only after they reach the HVAC return and would not offer protection from the virus while it travels from the infected person to the HVAC return. Accordingly, the first line of defense is keeping a passenger or driver infected with the virus from releasing it into the bus, and this can only be accomplished today with the use of face masks properly fit to each occupant before they enter the vehicle.

Following this, the team moved to the second objective of this project: trying to identify effective, cost-efficient technologies that could be utilized to mitigate live viruses from the cabins of transit buses.

Part 2: Virus Mitigation Study

For the second objective of this study, the team used three different live, bacteriophage viruses (Phi6, MS2, and T7) to test the effectiveness of different technologies in mitigating live viruses

from the air as well as surfaces inside bus cabins. The team adopted two testing methods: lab experiments and on-vehicle field testing, and conducted experiments using the different viruses, testing the different technologies in each of these two environments.

The tested technologies included the following: baseline cooling conditions, heating conditions at different temperatures (83˚F, 86˚F, 103˚F and 130˚F,), HEPA filters (MERV-17 and MERV-19), carbon filter (MERV-7), carbon filter with UVC light (MERV-7), photocatalytic oxidation filter with UVC, photocatalytic oxidation inserts with UVC, ionizer, positive pressure (0.5 inches of water column), and different antiviral materials (steel and copper surfaces, and different fabrics with different materials and percentages of cotton, copper, polyester, and graphene).

The team decided to use three different live, bacteriophage viruses to try to ensure the validity of the findings for mitigating the actual novel coronavirus, as well as other potential airborne viruses in general. Given that the team did not use the actual novel coronavirus, due to expected risks and health hazards, the team picked live viruses with different characteristics (varying similarities and differences) to the novel coronavirus, e.g. virus size, shape, and genome properties.

It was comforting that the results from both the lab experiments and the field tests were generally consistent.

With respect to technologies utilized to mitigate the virus from the air, the team identified that the photocatalytic inserts (99.2%), heating at very high temperatures (97.5%), UVC lights (97.1%), MERV-19 HEPA filters (96.7%), and photocatalytic filters (95%) performed best on average (across all experiments: lab and field, and all three live viruses).

With respect to technologies utilized to mitigate the virus from settling on surfaces, the team identified that positive pressure mitigated all viruses on surfaces by 100%. Moreover, copper foil tape and fabrics with a high percentage of copper mitigated the Phi6 virus by 99.7%; however, results were inconclusive with the other two viruses.

Post-Project Air Quality Exploratory Experiments

Upon the completion of the project and release of preliminary findings, the team received feedback about concerns of potential air quality hazards from the use of photocatalytic oxidation and UVC technologies. Specifically, there were concerns about possible toxic by-products from these two technologies (photocatalytic oxidation and UVC lights). Accordingly, the team acquired some additional funding and performed a few exploratory experiments to investigate the impact of the two top identified technologies (photocatalytic oxidation with UVC and UVC lights) on the release of toxic byproducts in the transit bus cabin air.

The team performed two groups of experiments (while the transit bus was static and in-motion on the freeway) and measured the concentrations of formaldehydes, ozone, and VOCs in the cabin.

The measurements did not record any differences in the concentrations of these three concentrations in the bus cabin air when these devices were retrofitted in the bus HVAC system (in comparison with when the HVAC system was running with the absence of these devices).

Further Work

Given the devastating impact of the COVID-19 pandemic worldwide and its significant effects on ridership and operations of transit systems, the team focused on performing this exploratory project and releasing the results of this work in a timely fashion. Accordingly, the scope of this project was highly constrained and limited in both budget and time. There is of course more research that still needs to b done. What follows are some examples of such further work.

With regard to airflow and circulation, the team investigated only a small set of buses. There are plenty of additional buses and vehicles that should be investigated, including passenger vehicles, transit vans, articulated buses, intercity coaches, and train carts. The team utilized smoke and steam to emulate viral movements carried by human breath. Further studies could analyze the similarities and differences between particle size distributions of these different mediums.

With regard to the virus mitigation study, the team utilized three different live, bacteriophage viruses with varied similarities and differences to the novel coronavirus. Additional research using the actual novel coronavirus could further demonstrate the validity of the findings of this work. Since the conclusion of this project, additional virus mitigation technologies have been introduced in the market. Evaluation of these technologies would add to the comprehensiveness of this work. In this study, the viruses were directly sprayed into the return of the lab and bus HVAC systems. Research on the impact of the distance of the viral source from the HVAC return would complement the findings of this project. Research on the possible spread of the virus from within the vehicle cabin to others outside of the vehicle upon opening bus doors at bus stops could be valuable. Additionally, research on critical passenger spacing and occupancy arrangements within transit vehicles could be highly worthwhile.

While the team believes that the top identified technologies are both effective and cost-efficient in mitigating viral spread in transit bus cabins, additional research on the actual life-cycle costs of retrofitting or developing bus HVAC systems with these technologies would be valuable.

While these findings may be applicable to any confined spaces with HVAC systems (e.g., classrooms, offices, homes, shopping malls, etc.), further research that is focused on these environments would be valuable.

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