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FTA RESEARCH
FEDERAL TRANSIT ADMINISTRATION

FTA Standards Development Program: Transit Bus Operator Temporary Barrier to Reduce COVID-19 Exposure

PREPARED BY
Center for Urban Transportation Research
Virginia Tech Transportation Institute

U.S. Department of Transportation
Federal Transit Administration

JULY
2022

COVER PHOTO

Cover image courtesy of Andrew Crum, VTTI

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

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14. ABSTRACT
The Virginia Tech Transportation Institute (VTTI) performed this research project under contract to the Center for Urban Transportation Research (CUTR) at the University of South Florida in support of the FTA Standards Development Program. The purposes of this project were to (1) demonstrate the production of a durable physical temporary barrier between the front and rear passenger compartment of a transit bus to reduce the exposure risk to COVID-19 for the operator and passengers, (2) perform an air flow test of the temporary barrier; and (3) share the results to maximize the positive impact to the public transportation system throughout the U.S. To test the air flow in the cabin and temporary barrier design, VTTI worked with two local transit agencies to procure several buses with different heating, ventilation, and air conditioning configurations. The tests were conducted during dedicated route service on surface streets and on a closed course at Virginia Smart Roads with no passengers other than the testing staff.

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Temporary bus barrier, reducing exposure in transit buses, air flow modifications in buses, COVID mitigation

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Abstract

The Virginia Tech Transportation Institute (VTTI) performed this research project under contract with the Center for Urban Transportation Research (CUTR) at the University of South Florida in support of the Federal Transit Administration (FTA) Standards Development Program. The purposes of this project were to (1) demonstrate the production of a durable physical temporary barrier between the front and rear passenger compartment of a transit bus to reduce the exposure risk to COVID-19 for the operator and passengers, (2) perform an air flow test of the temporary barrier, and (3) share the results to maximize the positive impact to the public transportation system throughout the U.S. To test the air flow in the cabin and temporary barrier design, VTTI worked with two local transit agencies to procure several buses with different heating, ventilation, and air conditioning configurations. The tests were conducted during dedicated route service on surface streets and on a closed course at Virginia Smart Roads with no passengers other than the testing staff.

Executive Summary

Information and prevention guidelines from the Centers for Disease Control and Prevention (CDC) show that the COVID-19 virus (SARS CoV-2) is transmitted from infected individuals when they exhale droplets and particles that contain the SARS CoV-2 virus. Then, through close contact or aerosol form, the virus spreads in a population.[1] To mitigate the transmission of COVID-19 and protect transit operators, who are a critical part of the public transportation infrastructure, transit agencies across the U.S. implemented temporary measures, some of which included restricting boarding to the rear doors, implementing frequent surface cleaning, issuing Personal Protective Equipment (PPE), and installing droplet barriers around the operator workstation. However, there are limitations to the effectiveness of these measures. For example, some transit buses are equipped with Americans with Disabilities Act (ADA) accessible ramps and/or lifts only at the front doors of the bus. Another limiting factor is the design of the heating, ventilation, and air conditioning (HVAC) system on a transit bus, which is designed to produce heating and cooling at one central location and circulate the air along the length of the bus. This design could spread infectious materials from infected individuals to other passengers and the operator, even if there is separation between them.

The Virginia Tech Transportation Institute (VTTI) performed this research under contract with the Center for Urban Transportation Research (CUTR) at the University of South Florida in support of the Federal Transit Administration (FTA) Standards Development Program. The purposes of this project were to (1) demonstrate the production of a durable physical temporary barrier between the front and rear passenger compartment of a transit bus to reduce the exposure risk to COVID-19 for the operator and passengers, (2) perform an air flow test of the temporary barrier, and (3) share the results to maximize the positive impact to the public transportation system throughout the U.S. To test the air flow in the cabin and temporary barrier design, VTTI worked with two local Virginia transit agencies, Blacksburg Transit (BT) in Blacksburg and Valley Metro (VM) in Roanoke, to procure several buses with different HVAC configurations. The tests were conducted on dedicated route service on surface streets and on a closed course at Virginia Smart Roads with no passengers other than the testing staff.

Objectives

Prior to the design and testing of the temporary barrier concept, the VTTI research team reached out to most transit bus manufacturers that produce buses for the U.S. (e.g., Gillig, New Flyer, Nova, Proterra) to seek design input and develop universal solutions, where possible. VTTI also engaged

[1] https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/sars-cov-2-transmission.html.

with CDC personnel and the Amalgamated Transit Union to ensure that this research activity would serve the best interests of the public and transit agency personnel. Each responded positively to this investigation of public transportation engineering controls for COVID-19. Following the input, objectives were set for the project:

1. Construct two prototypes that can be fitted to two different 40-ft transit buses with different ventilation configurations and test and identify the air flow during typical operations.
    A. Test one ventilation configuration on an older model transit bus HVAC system located in the rear of the bus with no fresh air intake.
    B. Test one ventilation configuration on a newer-model transit bus HVAC system that is roof mounted with fresh air intake near the bus operator workstation and the passenger area.
2. Analyze the air flow and air temperature in each bus configuration.
    A. Video recordings should be collected to demonstrate, with fog, mist, and/or strings (i.e., telltales), the air flow patterns around the bus operator workstation and temporary barrier for visualization.
    B. Variation of the bus ventilation flow factors should be measured.
    C. Measurements of ambient air temperature outside the bus and inside the bus along the length of the bus should be collected during each test.
3. Organize temporary barrier specifications and results of tests into technical briefings and distribute instructional or guidance reports and presentations as well as computer-aided design drawings and 3D models to agencies, manufacturers, and other researchers.

Vehicle Configuration and Barrier Build

VTTI worked with BT and VM to procure the buses used for testing. The primary test buses were two 40-ft New Flyer models with different HVAC configurations. The older 40-ft New Flyer bus (2009) had a rear-mounted HVAC system with no fresh air intake. The new 40-ft New Flyer bus (2014) had a forward roof-mounted HVAC system with a constant 20 percent fresh air intake. Both buses had adjustable fresh air intake and defroster at the operator workstation. The primary testing was conducted without a temporary barrier (designated baseline) and with a temporary barrier (designated barrier). In addition to the primary buses, a new model 35-ft Gillig bus (2019), provided by VM, was also tested. The testing on this bus was limited to the baseline configuration.

The temporary barriers were composed primarily of transparent polycarbonate and PVC piping to serve as the frame on which the polycarbonate sections of the temporary barriers were attached. The PVC piping was supported by attaching it to the stanchions near the middle of the passenger seating compartment and at the end of the ADA seating/securement area. Rubber feet were attached to the bottom of the temporary barriers to dampen forces that might be transferred from the chassis and floor of the bus through the temporary barriers. The temporary barriers in buses A and B used the same frame, but the polycarbonate sections were cut to match the profiles of buses A and B specifically. This was intended to reduce the variation in parts between bus configurations, focusing on matching the temporary barrier surface areas to the specific bus configuration.

Data Collection

The test plan was to conduct dynamic driving tests to identify air jets using the telltale method and air flow with fogging on two different transit bus HVAC configurations without a temporary barrier (baseline) and with a temporary barrier. The telltale method involved instrumenting each bus with approximately 40 sticks with two bright neon strings at the ends of each stick. The sticks were attached near each duct opening in the bus operator workstation, entry door, and passenger zones. Duct outlet air speeds on the two primary buses were also collected with an anemometer with and without the temporary barriers installed. The testing approach included testing with the driver window open and closed and the roof hatches open and closed. This led to the examination of exterior air flow impacts on interior air flow on the primary buses. Air jet and air flow testing were performed at three vehicle speeds—idling at 0 mph and driving on public and test track roads at 10 mph and 25 mph. In addition, informal cooldown temperature A/C measurements were collected on the primary buses with and without the temporary barrier installed after the fogging trials were completed. For the two non-primary buses, *ad hoc* measures were collected, including limited air jet and air flow videos at idling and 10-mph and 25-mph operating speeds.

Conclusions

The results of the observations and measurements are organized below according to the air flow objectives of the study. These settings may be considered by transit bus agencies for implementation depending on the bus configuration as equipped.

Objectives	Bus/HVAC Configuration Considerations	Optimal Bus/HVAC Settings
Maximize air dilution for bus operators and passengers	Windshield defrost vent fresh/recirculate	If equipped, set defrost vent to full fresh and defrost fan to high.
	Windows in passenger compartment	If equipped, open passenger windows depending on outdoor weather/ temperature.
	Front roof hatch	If equipped at or rear of front axle, open front roof hatch depending on outdoor weather/temperature.
	Rear roof hatch	Open rear roof hatch depending on outdoor weather/temperature.
	Bus operator workstation driver window	Close driver window.
Pressure barrier near bus operator for airflow management	Rear HVAC system; two-door bus entry; rear-mounted touchless fare system	Install temporary barrier near the bus front (i.e., behind ADA section) with minimum gaps (i.e., approx. 1 in.) to floor, walls, and ceiling to minimize cabin air mixture with bus operator workstation area.
	Bus operator workstation driver window	Close driver window to maintain positive pressure around the temporary barrier.
Reduce air flow from bus rear to front	Bus operator workstation driver window	Close driver window to reduce cabin air mixture (i.e., rear-to-front flow) during vehicle motion.
	Front roof hatch	If equipped near bus operator workstation, close front roof hatch to reduce cabin air mixture (i.e., rear-to-front flow) during vehicle motion.
Avoid impacting HVAC cabin temperature management	Bus–rear HVAC system	If equipped (based on limited outdoor cooldown temperature testing), the temporary barrier did not impact cabin temperature management.
	Bus–mid HVAC roof-mounted system	If equipped (based on limited outdoor cooldown temperature testing), the temporary barrier impacted cabin temperature management.

Section 1

Introduction

Background

Transit bus operations are critical to support transporting the public. During the COVID-19 pandemic, the need for transit was emphasized but also challenged. COVID-19 can be transmitted from infected individuals by both droplets and particles through nearby contact and as an aerosol. In response, transit agencies across the U.S. implemented temporary measures to reduce the number of close interactions (within a proximity of 6 ft) between transit bus operators and passengers. One method to limit close interactions for bus operators is to prevent front-entry door boarding access. In cases in which transit buses are equipped with ramps at the front door only, persons with disabilities are still allowed access through the front door. In either case, the bus operator (i.e., driver) is required to ensure that the person is secured on the bus, which often requires close contact with the passenger and their personal equipment (e.g., wheelchair). The best preventive measures for bus operators coming into close interaction with passengers include wearing Personal Protective Equipment (PPE), such as a mask and gloves, while interacting with passengers for short periods of time. Wearing PPE throughout the entire bus operator shift may not be practical or completely effective. Many transit agencies have implemented droplet barriers near the bus operator workstation that are intended to be manually or automatically closed while passengers board through the front door. These barriers can create glare or obstruct visibility of external rearview mirrors, so they need to be stowed out of the way when the bus is in motion. Beyond this, transit agencies have put into place frequent surface cleaning protocols between operation cycles. Another preventative measure is to restrict movement of passengers from the rear of the bus to the front of the bus with physical barriers.

Unfortunately, the ventilation systems on transit buses work similarly to those in large residential/ office buildings. That is, the heat and air conditioning are produced in one or two locations and circulated along the entire length of the bus to manage temperature and uniformly heat or cool the passengers and bus operator. Due to this design, the air of infected individuals on a 40- or 60-ft transit bus could be spread to other passengers on the bus and to the bus operator. Although evidence of this phenomenon is not widespread, the risk is apparent based on the study by Shen et al., (2020) which reported that a community outbreak among bus riders in China suggested that passengers who were seated as far as seven rows (or 4.5 meters) from an infected passenger became compromised.[2] One factor in this situation is presumably the air ventilation on the bus. Therefore, bus operators could be exposed to multiple individuals, even at significant distances, throughout the course of each shift due to the air circulation pattern on the bus.

[2] Shen, Y., Li, C., Dong, H., Wang, Z., Martinez, L., Sun, Z., ... & Xu, G. (2020), "Community Outbreak Investigation of SARS-CoV-2 Transmission among Bus Riders in Eastern China," *JAMA Internal Medicine*, 180(12), 1665-1671.

Problem Statement

To mitigate the problem of contaminated air circulating through the ventilation systems of transit buses, both long- and short-term solutions are needed. One long-term solution for bus operators would be enhancing existing security barriers (Option A) to extend forward to the windshield and up to the roof. An existing security barrier that was developed to protect drivers from physical contact is shown in Figure 1-1. Another solution is to design HVAC systems to always combine fresh air mixing and high-performance filtering for the bus operators. This longer-term solution can also be implemented for the passenger section of transit buses. However, due to the common spaces occupied by seated and standing passengers, additional controls may be necessary, such as designing air circulation to flow vertically to follow gravity rather than the current flow pattern that moves along the length of the bus.

Figure 1-1 *Example of low-floor transit bus with security barrier*

Until long-term solutions can be integrated into the design of transit buses, short-term solutions are needed to reduce the exposure of bus operators to infected passengers and passengers to other infected passengers. One short-term solution to protect bus operators is to create a barrier that physically restricts passengers from moving from the rear of the bus to the front of the bus during normal operations. Another potential short-term solution to protect bus operators and passengers is implementation of a physical barrier that creates unidirectional flow or positive pressure around the bus operator workstation and front section of the bus. Introducing such unidirectional flow from the front to rear of the bus, as opposed to circular flow, could improve the health of bus operators and passengers. Given that bus operators are on the bus over long periods of time each day, short-term solutions that maximize isolation and create positive air pressure around the bus operators should be prioritized.

This barrier concept was suggested by transit bus operator union representatives (e.g., Amalgamated Transit Union [ATU], Health and Safety) who helped to identify the need to limit physical interaction between bus operators and passengers while enhancing fresh air ventilation in response to COVID-19. The Virginia Tech Transportation Institute (VTTI) engaged with bus manufacturers, transit agencies, Centers for Disease Control and Prevention (CDC) personnel, and the ATU to ensure that this research activity would serve the best interests of the public and transit agency personnel. During development of a barrier concept, VTTI also discussed barrier concepts with engineers from light vehicle manufacturers who have experience designing and testing ventilation systems. Although the vehicles are very different, these engineers brought lessons learned on how to address the issue of air filtration and the protection of bus operators and passengers from viruses. VTTI also discussed the need with other transit agencies that are considering or testing bus barrier and ventilation configurations. Finally, VTTI consulted with an aerodynamics expert in low-speed air flow on the preliminary design concept of the barrier.

It was important to construct and test this barrier concept in transit buses to determine the feasibility and effectiveness of the barrier to provide unidirectional flow from the front of the bus to the rear. The prescribed tasks for this research were to construct barriers in two transit buses, perform physical flow visualization tests, and analyze and share the results. Additional studies should also be completed on other configurations of transit bus operator workstations, passenger compartments, and ventilation sources, such as rear/front and fresh/recycled. VTTI contacted most transit bus manufacturers that produce buses for the U.S. (e.g., Gillig, New Flyer, Nova, and Proterra) to seek to design input and develop universal solutions, where possible.

Based on the outcome in demonstrating unidirectional flow, the results of the proposed test and the parameters of the constructed barrier would be shared with other government agencies, public agencies, and research organizations throughout the U.S. to apply to similar bus configurations or evaluate on different bus configurations. This would be accomplished through channels such as webinars, conferences (online or in-person, as appropriate), and research and standards committee meetings. During the distribution of findings, VTTI integrated related and recent findings of other administrative, behavioral, and engineering controls for COVID-19 that, in conjunction with the results of this concept, may enhance the safety and health of transit bus operators and the riding public.

Objectives

1. Construct two prototypes that can be fitted to two different 40-ft transit buses with different ventilation configurations and test and identify the air flow during typical operations.
    a. Test one ventilation configuration on an older model transit bus HVAC system located in the rear of the bus with no fresh air intake.
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2. Analyze the air flow and air temperature in each bus configuration.
    a. Collect video recordings to demonstrate, with fog, mist, and/or strings (i.e., telltales), the air flow patterns around the bus operator workstation and temporary barrier for visualization.
    b. Measure variation of the bus ventilation flow factors.
    c. Collect measurements of ambient air temperature outside the bus and inside the bus along the length of the bus during each test.
3. Organize temporary barrier specifications and results of tests into technical briefings and distribute instructional or guidance reports and presentations as well as computer-aided design (CAD) drawings and 3D models, to agencies, manufacturers, and other researchers.

Section 2 Build and Test

Bus and HVAC Configurations

Table 2-1 lists all bus and HVAC configurations included in the ventilation test. Two buses were included in the original test plan—a 40-ft New Flyer with rear HVAC exhaust (bus A), shown in Figure 2 1, and a 40-ft New Flyer with roof HVAC exhaust (bus B), shown in Figure 2-2. Both buses were provided by Blacksburg Transit (BT), in Blacksburg, Virginia; Valley Metro (VM), in Roanoke, Virginia, provided the use of a third bus, a 35-ft Gillig with rear HVAC exhaust (bus C) shown in Figure 2-3.

Table 2-1 *Transit Bus and HVAC Model Configurations*

ID	Bus	Model	Year	HVAC Type	HVAC Make	HVAC Model
A	New Flyer 40-ft	SR-1360 D40LFR	2009	Rear	Thermo-King	T11
B	New Flyer 40-ft	SR-1840 XD40	2014	Mid/Roof	Thermo-King	RLF2-M13
C	Gillig 35-ft	22-68717-047	2019	Rear	Thermo-King	T14-M72A

Figure 2-1 *BT New Flyer 40-ft bus (bus A) configured with rear HVAC exhaust*

Figure 2-2 *BT New Flyer 40-ft bus (bus B) configured with forward roof HVAC exhaust*

Figure 2-3 *VM Gillig 35-ft bus (bus C) configured with rear HVAC exhaust*

Buses A and B differed primarily in their passenger HVAC systems. Table 2-2 provides a comparison of key bus components as equipped in the evaluated configurations. In Bus A, the HVAC exhaust that collects air for heating and cooling the passenger air as well as supplying air to the bus operator in the workstation, is located on the rearmost wall of the interior (see Figure 2-2). The HVAC exhaust in bus B that collects air for heating and cooling passenger and bus operator air is located on the roof above the Americans with Disabilities Act (ADA) mid-front section (shown in Figure 2-3). One additional difference in the passenger HVAC in bus B is the constant 20 percent mixture of fresh air that is not adjustable. While Bus C was built by a different manufacturer, the HVAC supplier is the same as for buses A and B. The HVAC exhaust for heating and cooling the passenger air in bus C operates similarly to bus A. The exhaust, located in the rear of the bus, is shown in Figure 2-4. The HVAC does not integrate fresh air in the mixture.

Table 2-2 *Transit Bus and Key Component Configurations*

ID	Bus	Passenger HVAC Type	Windshield Defrost	Roof Hatch Locations	Driver Auxiliary Fan	Passenger Windows
A	New Flyer 40-ft	Rear; 100% recirculate	Fresh/ recirculate	Front at front door; back at rear axle	Equipped	Fixed
B	New Flyer 40-ft	Mid/ Roof; 80% recirculate, 20% fresh	Fresh/ recirculate	Front at front door; back at rear axle	Not equipped	Fixed
C	Gillig 35-ft	Rear; 100% recirculate	Recirculate only	Front at front axle; back at rear axle	Equipped	Tilt open

Buses A and B have similarities in the body structure and driver defrost ventilation features. Buses A and B have options to select 100 percent fresh driver defrost, as shown in Figure 2-4 and Figure 2-5. These buses come equipped with driver defrost air exhaust that is adjustable by the bus operator to direct air from outside the front of the bus or from inside the bus near the dash and steering column. Bus C differs significantly from the other two buses in the HVAC. Bus C is not equipped with fresh air options for the driver defrost, as shown in Figure 2-6. Therefore, the source of the driver defrost air exhaust is limited to inside the bus near the dash and the fare box.

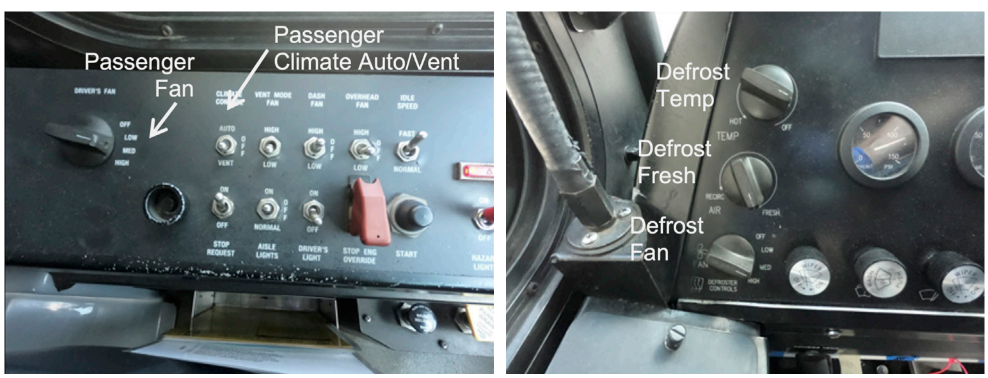


Figure 2-4 *Bus A equipped with driver defrost fresh air option but no fresh mixture in passenger*

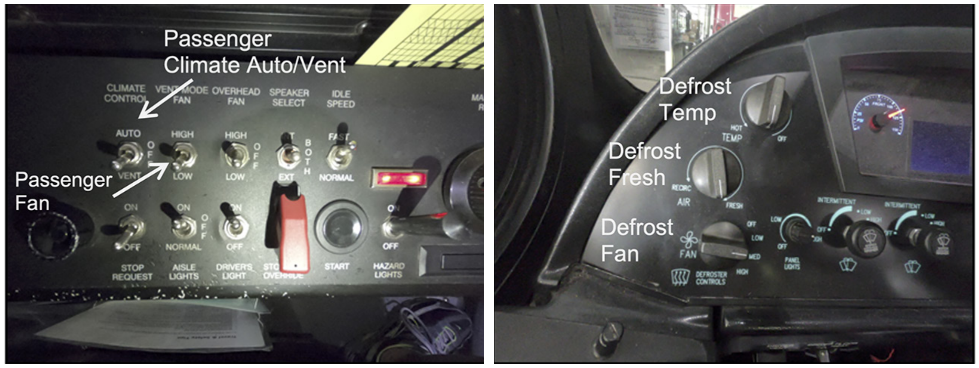


Figure 2-5 *Bus B equipped with driver defrost fresh air option and constant 20% fresh mixture in passenger air*

Figure 2-6 *Bus C equipped with passenger interior air recirculation (left) and driver defrost interior air recirculation (middle) only; source of exhaust for driver defrost air located on dash panel wall and in front of fare box (right)*

Both Buses A and B have front roof hatches located above the aisle and between the entry door and the bus operator workstation. Both buses also have rear roof hatches above the rear-wall bench seat, as shown in Figure 2-7 and Figure 2-8. The rear roof hatch in bus C is like buses A and B in relative location on the bus body; however, the front roof hatch in bus C is located significantly farther rearward compared to buses A and B, near the front axle in the ADA section, as shown in Figure 2-9.

Figure 2-7 *Bus A roof hatches located near bus operator workstation (left) and rear bench (right)*

Figure 2-8 *Bus B roof hatches located near bus operator workstation (left) and rear bench (right)*

Figure 2-9 *Bus C roof hatches located near front axle (left) and rear bench (right)*

Limited testing was performed with a Body on Chassis (BoC) bus at the request of BT. BT requested that VTTI test the effects of exterior air impacts on the direction of air flow inside the bus and near the bus operator. This bus was equipped with a passenger air HVAC on the body and traditional Chevrolet cut-away van HVAC fresh air driver defrost controls, as shown in Figure 2-10.

Figure 2-10 *BT BoC bus configured with cut-away van driver HVAC and separate roof-mounted rear passenger interior HVAC system*

Temporary Barrier Construction and Installation

To observe the impact of the temporary barrier on air flow, trials were run on buses A and B after the temporary barriers were installed. The design of the temporary barrier was completed prior to the application of this study. Images of the early prototype and final CAD model are provided in Appendix A., while the impacts of the temporary barrier on Federal Motor Vehicle Safety Standards (FMVSS) requirements are provided in Appendix B. The temporary barriers were composed primarily of transparent polycarbonate and PVC piping to serve as the frame on which the polycarbonate sections of the temporary barriers were attached. The PVC piping was supported by attaching it to the stanchions near the middle of the passenger seating compartment and at the end of the ADA seating/securement area. Rubber feet were attached to the bottom of the temporary barriers to dampen forces that might be transferred from the chassis and floor of the bus through the temporary barriers. The temporary barriers in buses A and B used the same frame, but the polycarbonate sections were cut to match the profiles of buses A and B specifically. This was intended to reduce the variation in parts between bus configurations, focusing on matching the temporary barrier surface areas to the specific bus configuration. Construction and parts lists are provided in Appendix C. The design concept is described below.

Each temporary barrier was preassembled into three sections, and final assembly was completed inside each bus. Any remaining gaps between the temporary barrier and bus sidewalls, stanchions, and other areas were filled with transparent box tape. Small (approximately 0.5 in.) gaps remained at the floor of the bus. Gaps were designed along the roof of the buses, with a 3-in. gap on the curb side of the bus and a 1-in. gap on the street side of the bus. This difference in gap was intentional to increase air flow on one side. The curb side was intended as the priority loading side for persons with disabilities who must load through the front door, since that side would provide convenience for communication and line of sight at a distance between bus operators and passengers with disabilities. Bus operators could speak with and instruct a passenger on how to secure themselves, when appropriate, and the bus operator could then briefly check or complete securement before returning to operation. This design consideration was intended to reduce the period necessary to secure passengers, while the barrier design was intended to provide full access to vehicle belts and securement, as required.

The temporary barrier installed for testing on Bus A, which has the rear exhaust HVAC configuration, is shown in Figure 2-11. The original temporary barrier installed for testing on bus B, which has the central roof-mounted exhaust HVAC configuration, is shown in Figure 2-12. The modified temporary barrier in bus B was made to extend the barrier below and in front of the roof-mounted exhaust with semi-rigid transparent vinyl. The modified temporary barrier is shown in Figure 2-13.

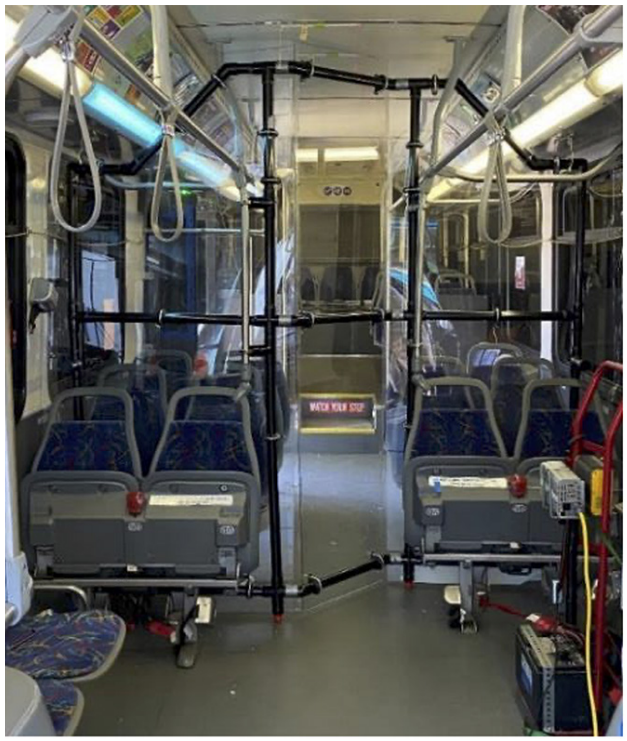


Figure 2-11 *Rear exhaust HVAC configuration (bus A) prototype temporary barrier with 3-in. ceiling gap on curb side (left) and 1-in. ceiling gap on street side (right)*

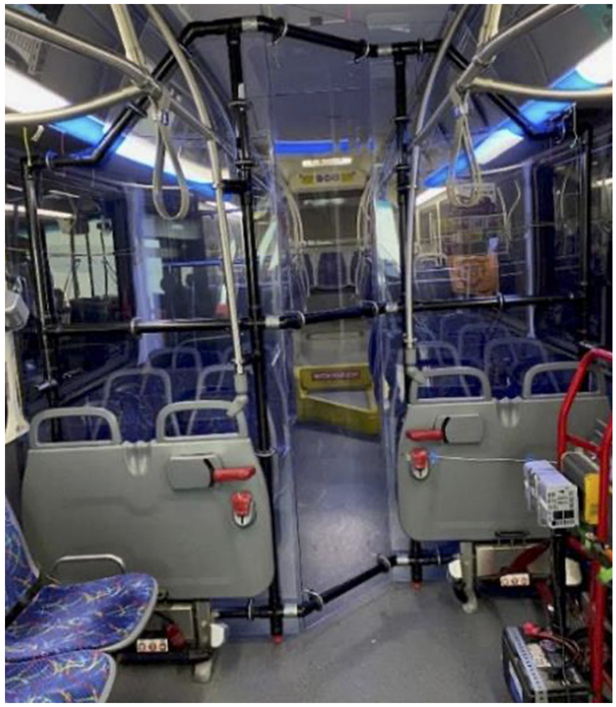


Figure 2-12 *Roof exhaust HVAC configuration (bus B) prototype temporary barrier, original with 3-in. ceiling gap on curb side (left) and 1-In. ceiling gap on street side (right)*

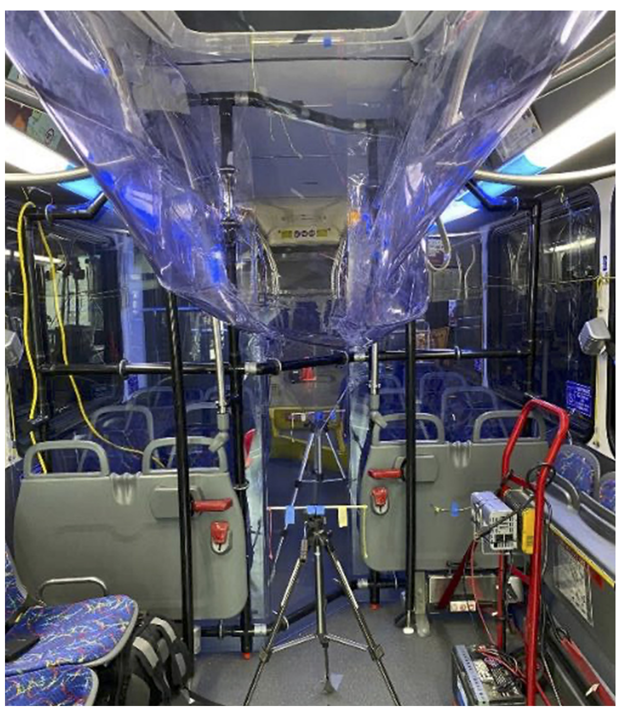


Figure 2-13 *Roof exhaust HVAC configuration (bus B) prototype temporary barrier, modified with hood surrounding roof exhaust*

Data Collection Overview

The original test plan was to conduct dynamic driving tests to identify air jets with telltales (i.e., strings) and air flow with fogging on two different transit bus HVAC configurations without temporary barriers (i.e., baseline) and with temporary barriers. These tests were completed, as listed in Table 2-3, while collecting reference exterior ambient and bus interior temperature measurements. Duct outlet air speeds on the two primary buses, (A and B) were also collected with an anemometer without and with the temporary barriers installed. In addition, informal cooldown temperature A/C measurements were collected on buses A and B without and with the temporary barrier installed after the fogging trials were completed. The testing approach included testing with the driver window open and closed and the roof hatch open and closed. This led to the examination of exterior air flow impacts on interior air flow on the primary buses, A and B, during the tests. Air jet and air flow testing were performed at three vehicle speeds—idling at 0 mph, driving on public and test track roads at 10 mph, and driving on public and test track roads at 25 mph.

Ad hoc measures were collected with bus C, including limited air jet and air flow videos at idling, 10 mph, and 25 mph. Exterior air impacts were also examined on bus C, as were anemometer measures of the duct outlet air speeds. Only baseline measures were collected for bus C without a temporary barrier. *Ad hoc* observations were also made with the BoC bus to examine air impacts at 25 mph only. Reference temperatures were not collected on bus C or the BoC bus. Descriptions of the testing instrumentation for all test methods is provided in Appendix D.

Table 2-3 *Summary of Measurement Types by Bus Configuration*

Vehicle, Experimental Control	Telltale Air Jet Videos	Fogger Air Flow Videos	Vehicle Speeds (mph)	Exterior Air Impacts	Temperature Status	Outlet Air Speeds	Cooldown (Informal)
Bus A, Baseline	x	x	0 / 10 / 25	x	x	x	x
Bus A, Barrier	x	x	0 / 10 / 25	x	x	x	x
Bus B, Baseline	x	x	0 / 10 / 25	x	x	x	x
Bus B, Barrier	x	x	0 / 10 / 25	x	x	x	x
Bus C, Baseline	x	x	0 / 10 / 25	x		x	
BoC, Baseline		x	25	x			

Telltale Air Jet Method

The air jet testing involved instrumenting each bus with approximately 40 sticks with two bright neon strings, called telltales, attached near each focused and distributed duct in the bus operator workstation, entry door, and passenger zones. Some strings were placed in locations that are not known to be near anticipated air flow or forced air zones. For example, telltales were attached to four tripods that were located 3 ft above the bus floor along the length of the bus from the standee line to the upper seating section. Special focused telltales were also located around the temporary barrier zone, even though no temporary barrier was installed in these baseline buses. Figures 2-14 through 2-17 illustrate the locations of telltales used to signal driver defrost airflow, passenger air flow in the bus operator workstation, passenger zone air flow, and air flow throughout the bus.

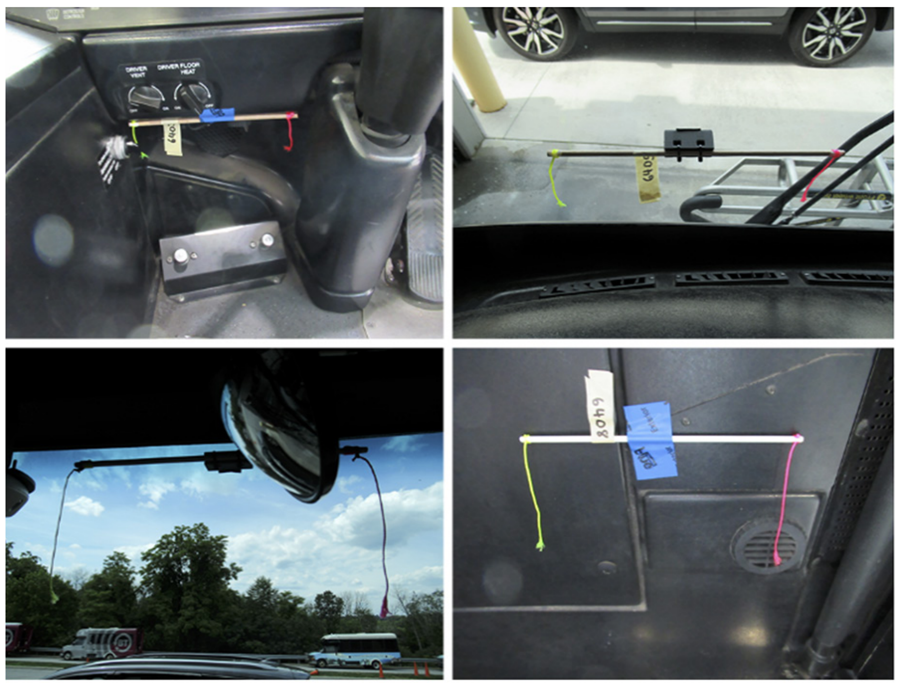


Figure 2-14 *Telltale locations near dedicated ducts from driver defrost on bus B—above pedals near steering column (upper left), lower windshield near defrost ducts (upper right), upper windshield (lower left), entry door duct (lower right)*

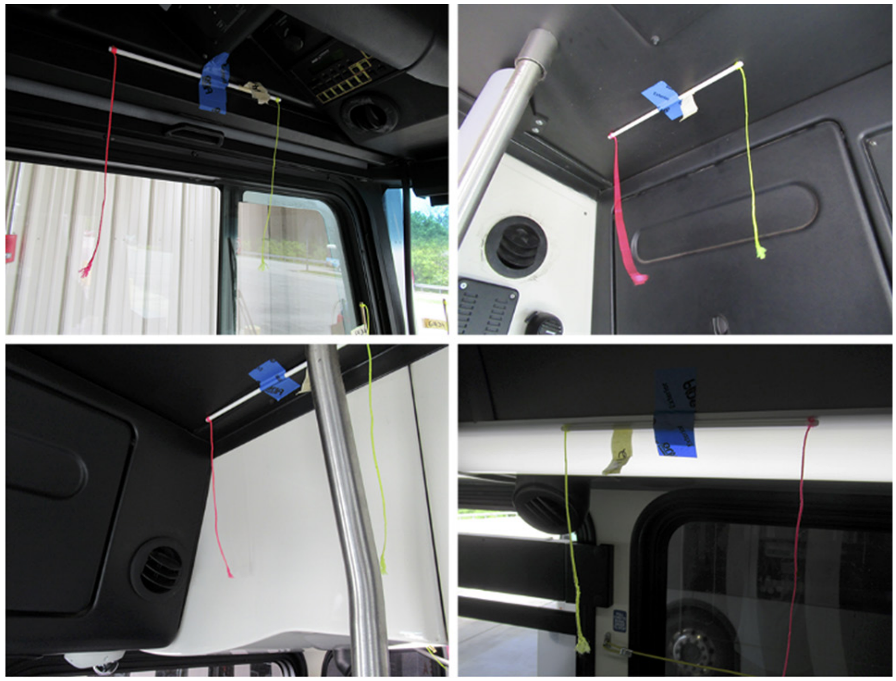


Figure 2-15 *Telltale locations near dedicated ducts in or near bus operator workstation from passenger HVAC on bus B—above bus operator (upper left), behind bus operator (upper right), above entry door (lower left), behind entry door and ADA section (lower right)*

Figure 2-16 *Telltale locations in passenger zone on bus B—passenger overhead console high (left upper and lower), passenger overhead console low (right upper and lower)*

Figure 2-17 *Other selected telltale locations on bus B—driver window glass and A-Pillar windshield (upper left), rear roof hatch (upper right), passenger HVAC roof-mounted exhaust (lower left), floor tripods (lower right)*

Handheld videos were collected by two experimenters on buses A and B while the buses were (a) idling at 0 mph, (b) driving on public roads at 10 mph, and (c) driving on public roads at 25 mph. BT selected roads on a local stretch that carried light traffic and had a long line of sight for operating safety as well as different sections of road that would be best for 10 mph and 25 mph operations. No fogging tests were performed on public roads. The air jet trials were organized to include combinations of driver defrost, passenger air, and both air systems active. (See Table 2-2 for a comparison of key components as equipped in the evaluated bus configurations.) Some form of interior air was activated during all trials. The air jet trials at the three speeds were completed with combinations of driver window open and closed, front and rear roof hatches open and closed, and both driver window and roof hatches open and closed.

Driver and passenger HVAC and auxiliary fan settings were established for the air jet testing. The driver defrost fan and driver booster fan (available in bus A only) were set to medium. The overhead windshield fan was set to low. The defrost was set to 100% fresh and the defrost heat was turned off. The passenger vent fan was set to low, rather than the only alternative, which was high. Due to the automatic passenger climate control system that modifies fan speed based on requested temperature and interior bus temperature, the bus climate control heat and A/C were not active. Since only one bus was equipped with the dash-mounted auxiliary fan, it was not activated during the air jet trials on either bus. Buses A and B are also equipped with a driver's vent to the outside of the front street-side corner of the bus. A knob that adjusts the vent from open to closed is located above the left foot well in the bus operator workstation. This duct was closed to eliminate unknown impacts to air pressure in the bus operator workstation.

During project planning prior to initiating air jet testing, the research team considered obtaining an auxiliary fan to mount in the rear roof hatch. The partnering bus manufacturer pursued this option via a traditional supplier of these fans but concluded that the fans could no longer be ordered by transit agencies and integrated into the roof hatch. The research team determined it was best to pursue testing without the fan and return to the option if results suggested it was critical to enhancing and directing air flow in the buses.

The air jet identification trials informed the fogging air flow trials. After the air jet trials were completed, the telltales were removed from the buses while the buses were put back in service. Due to the separate scheduling of the baseline air flow trials from the installation and scheduling of the temporary barrier air flow trials on the test track, only a few telltales were reinstalled for the trials with the temporary barrier installed on buses A and B. Based on the air jet identification trials, the research team recognized that telltales near most of the ducts would not provide significant new information beyond what was observed on the baseline trials. Some telltales were reinstalled in zones where the direction of air flow was not obvious. These telltales were located near the driver window, near the roof hatches, near the temporary barrier, and on the floor tripods near the temporary barrier.

Air Speed Velocity Method

The air velocities at each duct in buses A, B, and C were recorded. The driver defrost and booster fan, if equipped, were set at high speed. The passenger HVAC fan was set at high speed. All windows and hatches were closed during the air speed measurements. The buses were idling during these measurements. Many of the measurement locations of the ducts matched locations that were instrumented with telltales during the air jet observation. The air velocity was measured at each duct approximately 1 in. from the duct outlet. Peak measures of air velocity were recorded, and photos of each air speed measurement location were captured. Air speeds were also recorded near the temporary barrier location next to the ceiling on buses A and B without the temporary barrier (i.e., baseline) and with the temporary barrier installed. The direction of air flow through the anemometer was also noted.

Fogging Air Flow Testing

Measurement Model

The air flow testing was based on a simple visual observation model that is commonly used for exterior and interior air flow measures. During high-speed vehicle exterior aerodynamic tests used to develop body panels and components, a stream of fog is fed into airstreams around the vehicle to identify points and areas on the vehicle where air separates from the surface and can induce drag. The concept for this low-speed vehicle interior aerodynamics test is different since the fog is added to the air first and the air is induced after the fog is present. However, the measurement process is similar: an observer uses human judgment to identify the existence, direction, and to some extent, speed of the air flow. From these observations, the effects of intervening factors can be qualitatively judged to impact the direction of air flow.

It is important to clarify that this observation model is different from other quantitative or observational measures of air exchange. To measure exchange rates, it is important to insert a limited amount of fog into the confined space and measure how much fog is removed over time. In contrast, for this study, fog was periodically added during and between trials.

A limitation of this air flow observation method is that at some point the amount of fog within the confined space may reach equilibrium across the entire confined space and the observer can no longer judge where the air is moving. When that occurs, it is necessary to evacuate the space and start filling again. For this reason, the method including clearing the air in the bus between sets of trials. The method also included repeating trials with the fog machine running in the back of the bus and repeating the same trials with the fog machine running in the front of the bus. This served to provide judgment of air flow and change in air flow. For example, to test if air flows primarily from the rear of the bus to the front, if the fog machine is placed in the front of the bus, the fog should remain predominantly in the front of the bus. Likewise, if the fog machine is placed in the rear of the bus, then the fog should flow from the rear to the front of the bus until the fog reaches equilibrium.

This visual observation model was applied in the fogging air flow test to track the air that moves between sections and sides of the bus. The greater the density of fog inserted into the volume of the interior prior to the introduction of forced air due to HVAC or change in pressure, the more likely it is to observe the lack of air movement or change in air movement within the bus. The visual tracing fog was created with a glycerin fogger that provided continuous fog for approximately 1 minute before running through a cooldown cycle that lasted for 1–2 minutes.

Test Track Procedures

The air flow observation was performed on the Virginia Smart Roads (VSR) test track. The VSR is a closed test track operated by the Virginia Department of Transportation (VDOT) and consists of three sections of roadway built to VDOT specifications—Highway, Surface Street, and Rural Roadway. This study used the 2.5-mile Highway section for the continuous operation of air flow trials that lasted approximately 5 minutes each at speeds of 10 and 25 mph. During the trials, air flow was observed by fog tracing, which was also recorded by handheld videorecorders. Two research personnel were stationed in the bus, one at the front and one at the back. Bus operators from the local transit agencies served as the test drivers. Each testing trial was performed on one of two sub-sections on the VSR Highway. These sub-sections are identified in Figure 2-18 as Sub-section 1 and Sub-section 2.

Safety protocols were established due to possible visibility obstruction due to the fogging. First, a researcher was stationed between the two sub-sections used to run trials as a lookout to confirm the roadway was clear in case any wildlife entered the test track. The personnel in the lookout vehicle remained in radio contact with the research personnel on the buses during all trials. If radio communication could not be confirmed during each run, the trial and vehicle were stopped. The third sub-section includes two bridges. Due to the possibility of obscured visibility, none of the air flow trials were performed on the bridges at the southeast end of the Highway section. The test drivers were also instructed that they were always in control of the vehicle and experimentation could be stopped or some other approach could be taken to improve visibility. For example, at any time, drivers could open a window in trials where the window was closed. However, no test driver interruptions to trials were necessary during testing. The protocol for vehicle operations and testing personnel health was approved by the VTTI Safety Committee prior to all testing.

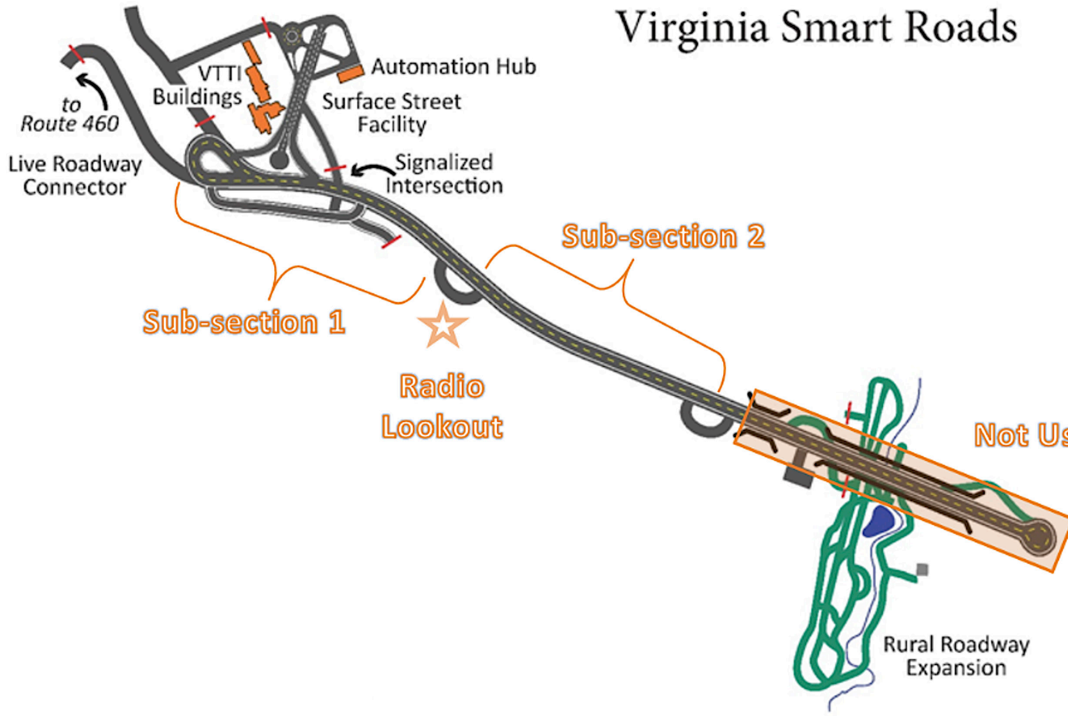


Figure 2-18 *Highway sections of VSR used during fogging air flow testing*

Air Flow Testing Method

Four buses were run through air flow testing. One bus configuration (bus B,) was run through repeat trials after modifications were made to connect the temporary barrier to the roof HVAC exhaust. Passenger windows on buses A and B were covered and taped with black plastic to create high contrast for video recordings inside the bus while testing in daylight hours. Handheld videos were collected by two experimenters on the buses while the buses were idling at 0 mph, driven on the VSR Highway at 10 mph, and driven on the VSR Highway at 25 mph. A video file was created for each trial on the two handheld video cameras. One additional static video camera was mounted on the curbside of the bus and was run continually. Video files on the static video camera typically spanned every set of six trials to provide evidence of long-term fog levels across trials. A sample frame from a video recorded by an experimenter in the rear of the bus while the fogger was positioned in the front of the bus is provided in Figure 2-19. A sample frame from a video recorded by an experimenter in the front of the bus while the fogger was positioned in the rear of the bus is provided in Figure 2-20. The air flow trials were organized to include combinations of driver defrost, passenger air, and both air systems active. Some form of interior air was activated during all trials. The air flow trials at the three speeds were completed with combinations of driver window open and closed, front and rear roof hatches open and closed, and both driver window and roof hatches open and closed. The aggregated matrix factors for the air flow testing are provided in Table 2-4.

Figure 2-19 *Baseline air flow testing video sample frame collected from rear of bus with fogger operating in front of bus*

Figure 2-20 *Baseline air flow testing video sample frame collected from front of bus with fogger operating in rear of bus*

Table 2-4 *Air Flow Testing Matrix of Bus Configuration and Settings, Barrier, and Locations of Fogging*

Bus	Barrier	Speeds (mph)	Roof Hatches	Driver Window	HVAC	Fogging Location
A	Baseline	0 / 10 / 25	Open, closed	Open, closed	Defrost, passenger	Front & rear; rear-only 0 mph
A	Barrier	0 / 10 / 25	Open, closed	Open, closed	Defrost, passenger, both	Front & rear; rear-only 0 mph
B	Baseline	0 / 10 / 25	Open, closed	Open, closed	Defrost, passenger, both	Front & rear; rear-only 0 mph
B	Barrier	0 / 10 / 25	Open, closed	Open, closed	Defrost, passenger, both	Front & rear; rear-only 0 mph
B	Modified barrier	0 / 25	Open, closed	Open, closed	Defrost, passenger, both	Front & rear 0 mph; rear-only 25 mph
C	Baseline	0 / 10 / 25	Open, closed	Open, closed	Defrost, passenger	Rear-only
BoC	Baseline	25	Open, closed	Open, partial, closed	Defrost, passenger	Rear-only

Driver and passenger HVAC fan settings were established for the air flow testing. The driver defrost fan and driver booster fan (available in buses A and C) were set to high. Auxiliary fans were inactive during the air flow testing. The driver defrost was set to 100% fresh and the defrost heat was turned off. The passenger vent fan was set to high. Due to the automatic passenger climate control system that modifies fan speed based on requested temperature and interior bus temperature, the bus climate control heat and A/C were not active. The driver vent to the outside of the front street-side corner of the bus was closed to eliminate unknown impacts to air pressure.

Examples of the bus air flow testing in progress are provided in Figures 2-21, 2-22, and 2-23. In two of the images, the buses were rolling, and fog can be seen exiting the rear roof hatch during testing trials. Prior to the beginning of each trial, the fogging machine was activated to establish fog in the front or back of the bus, depending on the trial. Baseline trials without a temporary barrier were run consecutively with each combination of bus speed, roof hatch setting, and driver window setting. Trials with the temporary barrier installed were also run consecutively with each combination of bus speed, roof hatch setting, and driver window setting. The bus was stopped to open and close the roof hatches or reposition the fogging machine in the front or rear of each bus. Typically, the test driver allowed the bus to continue rolling at the beginning of each trial while switching between HVAC modes and driver window positions. The experimenter in the front or back added additional fog at the beginning of and during trials.

Fog was added intermittently based on the operating limits of the fogging machine and the experimenter's opinion as to whether more fog was necessary to trace air flow. The bus was periodically stopped to evacuate the fog if it became too diffuse to allow the experimenters to judge air flow. Occasionally, trials were repeated when the researchers observed a significant point about the air flow and wanted to confirm the first observation.

Figure 2-21 *BT (bus A) during air flow testing on VSR Highway section*

Figure 2-22 *BT (bus B) during air flow testing on VSR Highway section; fog visible exiting bus rear roof hatch*

Figure 2-23 *VM (bus C) during air flow testing on VSR Highway section; fog visible exiting bus rear roof hatch*

Air Flow Reference Temperature Method

During baseline and temporary barrier fog testing trials with buses A and B, outside ambient temperatures and interior bus temperatures were recorded at the beginning of every set of three trials. The ambient temperatures were identified using an online weather app on the experimenter's smartphone. The ambient temperature and cloud cover were noted along with the time of day for every set of three trials. Interior temperatures were recorded for reference using the digital thermometer with thermocouples located in four locations along the length of the bus. Figure 2-24 shows the device and locations of the thermocouples.

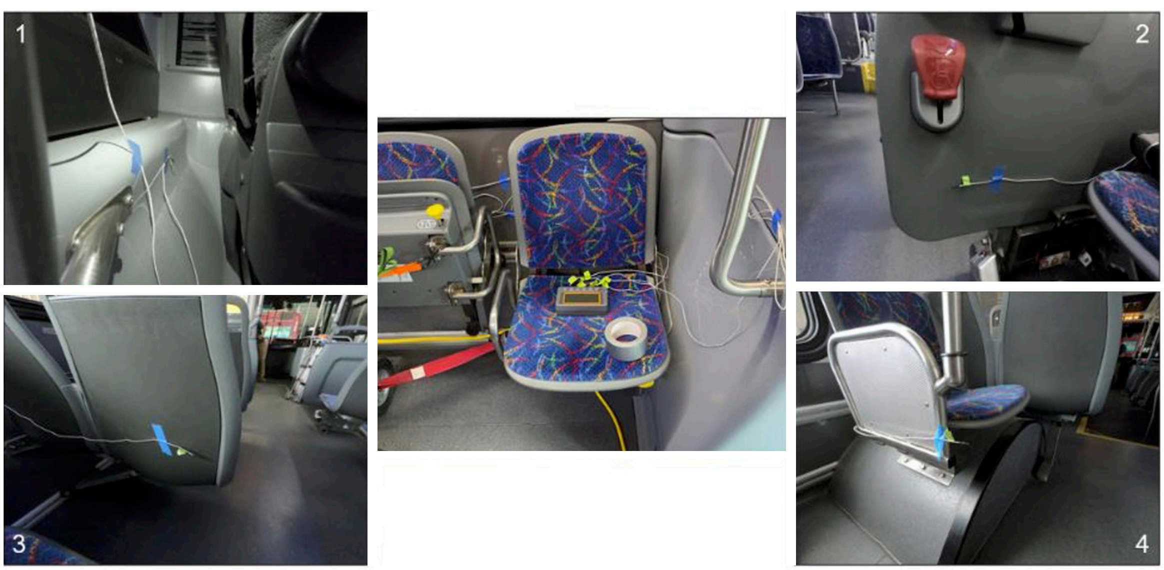


Figure 2-24 *Instrumentation of thermocouples on bus B—T1 – behind driver seat, T2 – modesty panel forward of barrier, T3 – seat rearward of barrier, T4 – upper seating area, center – digital thermometer measurement device*

Informal Cooldown Temperature Method

Informal bus cooldown performance was also recorded after air flow testing trials while the buses were idling and without any temperature or humidity controls at the beginning and throughout the cooling period. After each baseline or temporary barrier set of air flow trials was completed, the temperatures of buses A and B were elevated due to the summer weather. The thermocouples used for reference measures during the air flow testing trials were left in each bus while it was idling at 0 mph. The driver window and hatches were closed during all cooldown periods. Additionally, the driver defrost was active with high fan modes, and the passenger A/C was turned on. Recordings of the internal bus temperatures across the four locations were captured every minute for 10 minutes. The doors were closed during cooldown on both baseline and temporary barrier measures on Bus A. Due to the constraints of test scheduling on bus B, the doors were left open during cooldown periods for both the baseline and with temporary barrier measures.

Section 3

Analysis

Telltale Air Jet Observations

Some conclusions from the combination of HVAC, vehicle speed, and exterior panel openings were immediately obvious to the researchers who were present and collecting video during all air jet trials without the temporary barrier installed on buses A and B. Video review confirmed the research team's observations.

The observations on buses A and B were as follows:

1. The exterior panels and air flow outside the buses impacted the air flow inside the bus. The best example of this was the significant effect of an open driver window on the air jet activity at the rear roof hatches. The telltales attached near the rear roof hatches hung idle until the driver windows were opened, at which time the telltale strings moved continually and could be observed to be drawn towards the front of the bus.
2. The direction of air near the driver windows was idle or moving out of the windows, not into the bus except on turns or during heavy wind gusts.
3. The opening or closing of the driver windows did not appear to have a strong impact on air jets at the front roof hatches. No presence of air jets was observed in the telltales mounted near the front roof hatches. The front roof hatches were expected to scoop air into the bus, but this was not observed with any combination of HVAC or exterior panel settings.
4. There was a lack of air jets 3 ft above the floor along the length of the buses on lower and elevated floors.
5. There was a lack of air jets near the floor on the bus operator workstation platforms.
6. There was significant passenger air blowing above the entry doors on the curb side and above the bus operator workstation on the street sides with only the passenger HVAC air active.
7. There was a lack of air jets moving into the open front roof hatches. In contrast, the hatches appeared to exhaust air on buses A and B unless the driver window was open.

These observations were discussed with the research team prior to air flow testing with fogging and prior to installation of the temporary barriers. VTTI met through a web meeting with Dr. Breidenthal, project consultant on low-flow aerodynamics, and Brian Sherlock, Health and Safety engineer with the ATU, to review findings of the telltale identification of ventilation air jets without the temporary barrier on buses A and B prior to the air flow testing without and with the barrier. The group also discussed the settings used on the driver defrost, passenger vent fan and the dash- and overhead-mounted auxiliary fans near the windshield during the air jet identification trials. It was concluded that for air flow testing with fog, it would be best to accelerate air using high settings for defrost and passenger vent as much as possible to demonstrate flow direction based on visual evidence from the fog.

The group determined the best approach for HVAC settings during the fogging air flow testing. Through the air jet testing, it became apparent to the research team that features of the bus HVAC, fan, and exterior panels should be carefully controlled to organize the flow in the bus. Not every feature that moves air in the buses cooperates to move the air or move the air in the intended direction to reduce exposure to potential viral agents, which is away from bus operators. For example, the auxiliary fans were recognized to merely create churn in the air flow near the bus operator workstation. That may be beneficial for removing condensation on the windshield, but not supportive of this air flow organization approach. Therefore, the auxiliary fans in the front of the buses were removed from future air flow tests.

Air Speed Velocity Measures

Tables 3-1, 3-2, 3-3, and 3-4 list the air speed measures on buses A, B, and C at baseline and bus A and B with the temporary barrier installed. The measures are organized by the area of the bus, the source of supplied air, and the duct or other location on each bus. Experimenters observed that some ducts were susceptible to significant variance in air speed measures—in the range of ±0.5 meters per second—depending on how the experimenter positioned the anemometer at the duct outlet. With other ducts, it was simple to reproduce measurements. The most difficult ducts were those through which the outlet of the duct producing the air jet was not obvious based on visual inspection. The air speed measurements of the ducts above the passenger seats were difficult to measure consistently, as were measurements on general zones in the windshield coming from the driver defrost air source. Therefore, conclusions about the impact of the temporary barriers based on the change in air speed should made be cautiously.

Table 3-1 *Air Speed Measures Organized by Source and Duct Locations on Buses A, B, and C at Bus Operator Workstation*

Area	Supply Source (Speed Setting)	Duct / Location of Measurement	Bus A Base (m/s)	Bus A Barrier (m/s)	Bus B Base (m/s)	Bus B Barrier (m/s)	Bus C Base (m/s)
Bus Operator Workstation	Defrost (high)	Driver window (closed)	0.7	0.5	0.3	0.3	0.0
	Defrost (high)	Windshield driver A-pillar	2.4	2.1	0.3	0.5	2.3
	Defrost (high)	Windshield high, SS	1.1	1.3	0.3	0.3	0.0
	Defrost (high)	Windshield low, SS	2.5	2.5	2.1	1.8	1.3
	Defrost (high)	Windshield high, CS	0.9	0.9	0.7	1.6	0.5
	Defrost (high)	Windshield low, CS	2.4	2.4	2.9	2.1	2.5
	Defrost (high)	Windshield defrost vent, SS	7.3	7.3	4.8	4.3	4.0
	Defrost (high)	Windshield defrost vent, CS	7.3	7.3	4.8	4.4	4.0
	NA	Windshield aux fan, CS (high)	5.8	5.8	9.1	8.2	-
	Defrost (high)	Driver left footwell	2.0	2.0	-	0.3	0.0
	Defrost (high)	Driver right footwell	0.9	1.4	0.7	0.8	0.2
	Booster fan (high)	Above driver (booster), front	10.1	10.1	-	-	21.9
	Booster fan (high)	Above driver (booster), back	14.2	14.2	-	-	-
	Passenger (high)	Above driver (no boost/off)	1.3	-	11.1	12.2	2.5
	Passenger (high)	Behind driver seat, top	4.1	3.5	12.4	-	-
	Passenger (high)	Behind driver seat, middle	2.4	2.1	-	13.4	-
	Passenger (high)	Behind driver seat, bottom	2.1	1.8	-	-	-

SS = street side of bus, CS = curb side of bus

Table 3-2 *Air Speed Measures Organized by Source and Duct Locations on Buses A, B, and C at Front Entry Door and Passenger Seats, Street Side*

Area	Supply Source (Speed Setting)	Duct / Location of Measurement	Bus A Base (m/s)	Bus A Barrier (m/s)	Bus B Base (m/s)	Bus B Barrier (m/s)	Bus C Base (m/s)
Entry Door (Curb Side)	Defrost (high)	Entry door on dash, CS	4.4	4.4	2.4	2.7	6.0
	Passenger (high)	Above entry door, high	4.1	3.5	11.4	10.5	-
	Passenger (high)	Above entry door, low	3.1	2.9	-	-	-
Passenger Seats, Street Side	Passenger (high)	Above ADA seating, CS	-	-	12.7	11.8	-
	Passenger (high)	Above front seats, high	1.6	1.1	2.0	1.4	1.1
	Passenger (high)	Above front seats, low	2.1	1.6	3.5	1.5	1.8
	Passenger (high)	Above middle seats, high	0.8	1.2	2.1	1.8	1.5
	Passenger (high)	Above middle seats, low	1.9	2.2	2.1	1.3	2.5
	Passenger (high)	Above rear-upper seats, high	1.3	1.8	1.4	1.1	0.5
	Passenger (high)	Above rear-upper seats, low	3.0	3.4	2.5	1.5	2.5

SS = street side of bus, CS = curb side of bus

Table 3-3 *Air Speed Measures Organized by Source and Duct Locations on Buses A, B, and C at Passenger Seats, Curb Side and Center Aisle*

Area	Supply Source (Speed Setting)	Duct / Location of Measurement	Bus A Base (m/s)	Bus A Barrier (m/s)	Bus B Base (m/s)	Bus B Barrier (m/s)	Bus C Base (m/s)
Passenger Seats, Curb Side	Passenger (high)	Above front seats, high	1.8	1.6	1.0	0.8	0.7
	Passenger (high)	Above front seats, low	2.1	1.9	2.4	3.8	3.2
	Passenger (high)	Above middle seats, high	1.4	1.0	1.5	2.2	1.5
	Passenger (high)	Above middle seats, low	0.9	2.1	2.2	1.4	4.7
	Passenger (high)	Above rear-upper seats, high	2.6	2.8	1.0	1.7	0.6
	Passenger (high)	Above rear-upper seats, low	4.3	5.5	2.7	2.3	2.0
Center Aisle	NA	Front floor, 3-ft tripod	0.0	0.0	0.0	-	-
	NA	Barrier front floor, 3-ft tripod	0.0	0.0	0.0	0.0	0.0
	NA	Barrier rear floor, 3-ft tripod	0.0	0.0	0.0	0.0	0.0
	NA	Rear elevated floor, 3-ft tripod	0.0	0.0	0.0	-	-

SS = street side of bus, CS = curb side of bus

Table 3-4 *Air Speed Measures Organized by Source and Duct Locations on Buses A, B, and C at Temporary Barrier*

Area	Supply Source (Speed Setting)	Duct / Location of Measurement	Bus A Base (m/s)	Bus A Barrier (m/s)	Bus B Base (m/s)	Bus B Barrier (m/s)	Bus C Base (m/s)
Around Temporary Barrier	NA	Front of barrier, high 3-in., CS	0.0	2.4*	0.2	3.7	0.0
	NA	Front of barrier, low 3-in., CS	2.3	1.5*	0.0	3.5	0.0
	NA	Front of barrier, ceiling, center	0.0	0.0	0.0	3.1	0.0
	NA	Front of barrier, high 1-in., SS	0.0	1.8*	0.0	3.7	0.0
	NA	Front of barrier, low 1-in., SS	1.4	0.5*	0.3	1.6	0.0
	NA	Rear of barrier, high 3-in., CS	-	4.0*	-	3.3	0.0
	NA	Rear of barrier, low 3-in., CS	-	3.4*	-	3.3	0.0
	NA	Rear of barrier, ceiling, center	-	2.0*	-	2.2	0.0
	NA	Rear of barrier, high 1-in., SS	-	3.4*	-	3.1	0.0
	NA	Rear of barrier, low 1-in., SS	-	2.3*	-	1.0	0.0

SS = street side of bus, CS = curb side of bus
*Air flow measured above passenger seats was typically moving from back of bus to front. However, air flow on bus A with barrier installed flowed in reverse

The range in sources and locations for air flow in the bus operator area demonstrate a large range in options to supply air around the bus operator. Despite this variety of sources, it is important to emphasize that options have been provided for bus operators to increase air flow to assist in personal heating by activating defrost heat. The same is not true for cooling; bus operators can turn on additional fans to move air that might provide cooling, but there are no independent sources of A/C-treated air for the bus operator. The bus operator can increase the supply of heated or cooled air from the passenger HVAC system, but that system is always blowing air onto the operator and cannot be shut off by the bus operator without shutting off the entire passenger HVAC system. Furthermore, the air speeds did not appear to be affected by the presence of the temporary barrier. The air speed measurements in the bus operator workstation with the temporary barrier installed on buses A and B both decreased and increased compared to measurements without the barrier.

The constant supply of air around the bus operator workstation, observed by the research team whenever the passenger HVAC systems were active, highlights the importance of filtering the air in the passenger compartment and HVAC exhaust with a high Minimum Efficiency Reporting Value (MERV) rating that might reduce exposure for passengers and bus operators. One alternative that was conceived by the research team to reduce exposure for bus operators would be to increase filtering locally near the front of the buses inside the channels that carry the air from the rear or middle of the buses to the bus operator workstations and entry doors.

One important distinction between buses A and B is that bus A had a booster fan above the bus operator that can increase the flow of air from the passenger compartment from 1.3 m/s, when the booster is off, to 14.2 m/s when the booster is set on high. Bus B did not have this feature, and the air from the passenger HVAC always flows through that duct at approximately 11.1 m/s (baseline) when the passenger HVAC fan was set on high. Bus C has a booster fan that works like Bus A, except bus C has a hole in the component box surrounding the booster fan to assist in air movement near the windshield. Buses A and B also had ducts above the entry door that supply air from the passenger HVAC.

The ducts throughout the passenger compartment are implemented more consistently across the buses. Like the measurements in the bus operator workstation, the air speed measurements both increased and decreased across the two sides of the passenger ducts between the baseline and temporary barrier configurations on both buses A and B.

The most interesting observation was on bus A with the temporary barrier installed. Both the air speed and direction of flow were recorded near the barrier area for baseline and temporary barrier configurations. The experimenters noted, using the anemometer to measure air speeds, that the air in the area above the passenger seats on both curb and street sides of the bus moved forward in the bus. When the temporary barrier was installed, similar air speeds were measured in the same zones, but the air was flowing rearward. Likewise, the presence of the barrier made it possible to measure air speeds from the front of the barrier and from the rear of the barrier. The air speeds were higher at the rear of the barrier than at the front, demonstrating the shearing flow of air near the surface of the temporary barrier. This observation highlights the change in pressure possible when a large temporary barrier is installed on a bus with a rear HVAC configuration. Not only did the temporary barrier separate air space in the front of the bus from the rear of the bus, but the air appears to be organized to flow rearward rather than forward or both forward and rearward due to changes in pressure.

Fogging Air Flow Observations

VTTI researchers met again with Dr. Breidenthal and a representative from the ATU through a Web meeting in July 2020 to share videos of the air flow results from two bus configurations and to seek input on modifications and additional runs. The group reviewed videos of fog air flow movement that illustrated air flow and changes in air pressure due to the temporary barrier. The group also showed videos of anemometer measurements that clearly demonstrated the direction of air flow from front to back near openings along the top, sides, and bottom of the temporary barrier.

Similar to the telltales, some conclusions on the air flow measurements based on the combination of HVAC, vehicle speed, and exterior panel openings were immediately obvious to the researchers who were present and collecting video during all air flow trials without the temporary barrier installed. Video review confirmed the research team's observations. The observations are organized according to the air flow objectives of the study, which were to:

A. Maximize fresh air inside bus to assist in dilution of viral agents that may be present.
B. Produce a pressure differential at front of bus to encourage flow from front to back.
C. Identify methods to reduce air flow from back to front and consider implications for HVAC filtering.

A. Maximize Interior Air Dilution

Observation A1: Based on information from the HVAC supplier about the systems equipped on the buses included in the study, some older model buses (bus A, 2009) come equipped with the option to set the driver defrost at 100% fresh, though the passenger air is exclusively recirculated from interior air. Some newer model buses (bus B, 2014) from the same bus manufacturer have the option for 100% fresh in the driver defrost air and standard 20% fresh in the passenger air. An HVAC configuration in a recent model (bus C, 2019) bus built by a different manufacturer had no fresh air option for the driver defrost air or the passenger air (see Figure 3-1). If interior air filtration and control of outside air is the priority, rather than dilution of interior air, the design decision to reduce or eliminate the amount of outside fresh air that infiltrates the interior air may be the right balance when seeking to separate passengers and bus operators from external emissions and particulates. In situations where it is desirable to introduce outside air to dilute the possible presence of viral agents, then the option to add more exterior air may be an important design and operating consideration.

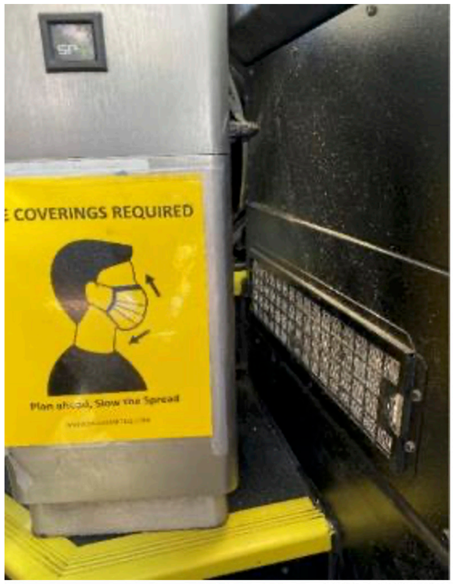


Figure 3-1 *Bus C driver defrost recirculation dash exhaust screen*

Observation A2: Buses can be configured with passenger windows that open in old and newer model buses. Some transit agencies order the passenger windows sealed shut, and others have chosen to seal older model bus windows for security. Passenger windows that open can be an important option to bus riders to increase air dilution, especially if confronted by another rider who might be expressing viral symptoms. Bus C is equipped with passenger windows that open. Experimenters observed, under limited trials, that the passenger windows quickly evacuated fog when open, even at low speeds (e.g., 10 mph). This solution may dilute the air in the entire bus, thus reducing exposure for bus operators as well (see Figure 3-2). However, it should be noted that this solution for dilution would be difficult for the transit agency and bus operators to control regardless of when dilution is desirable. Additionally, passenger windows may not support other objectives (i.e., Objective B) to organize air flow from front to back away from the bus operator.

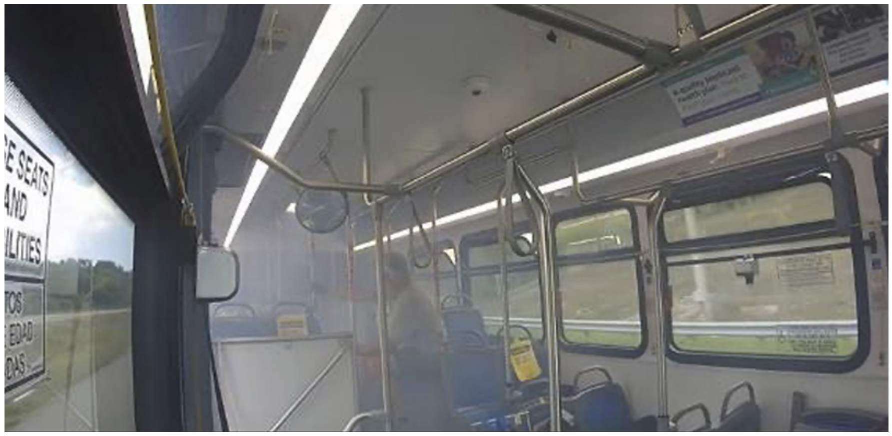


Figure 3-2 *Video sample of bus C with passenger windows evacuating fog*

Observation A3: Roof hatches located behind the bus operator workstation near the front axle can scoop or pull air into the bus, increasing the dilution of interior air (see Figure 3-3) without drawing air forward near the bus operator workstation.

Figure 3-3 *Bus C, open front roof hatch near front axle, telltales blowing rearward due to air entering*

Observation A4: This observation is complementary to Observation C2. If the driver window is closed and the rear hatch is open while the passenger rear exhaust HVAC air is active, the pressure of the passenger air system causes the air to flow into the bus through the rear hatch. This increases dilution in the air flowing throughout the passenger air system, which also will increase dilution for the bus operator workstation (see Figure 3-4).

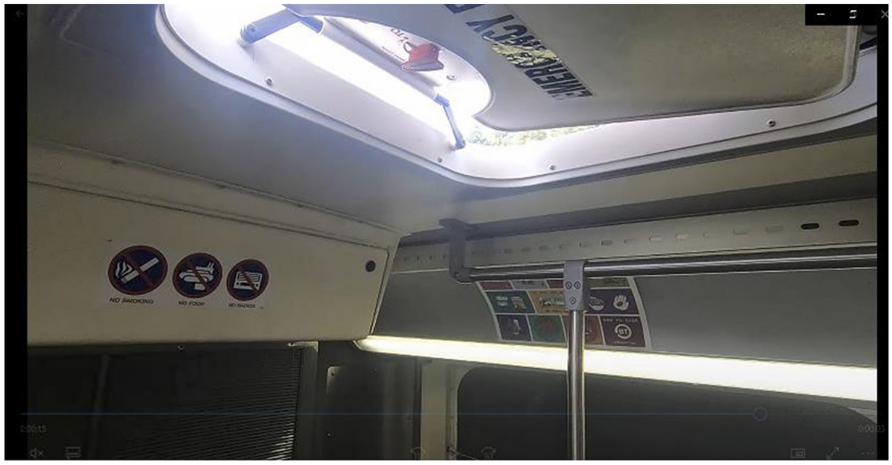


Figure 3-4 *Bus A, demonstrating fog drawn into bus through rear hatch with driver window closed and passenger rear HVAC exhaust on*

B. Produce Positive Pressure Differential at Front

Observation B1: A positive pressure differential can be produced at the front of the bus when a temporary barrier is implemented on a bus equipped with a rear exhaust HVAC, causing the air to flow from front to back when the driver window is closed. This pressure differential was observed both with driver defrost air only (see Figure 3-5) and passenger air only (see Figure 3-6).

Figure 3-5 *Bus A, fog flowing from front to back on curb side of bus with driver defrost air only*

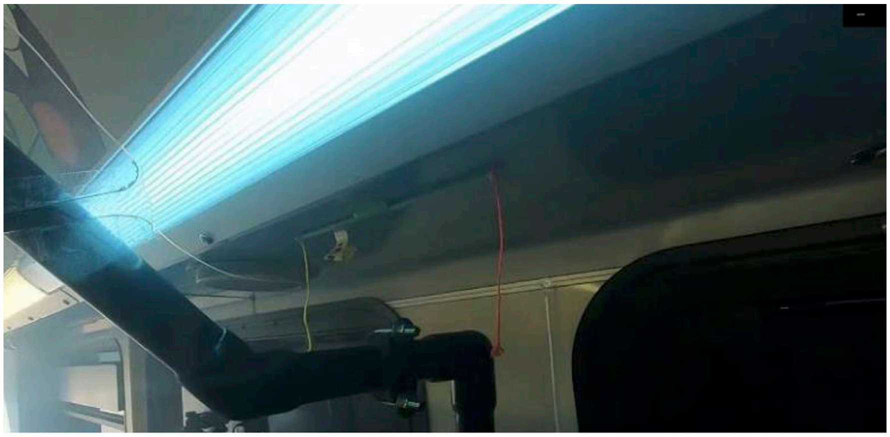


Figure 3-6 *Bus A, fog flowing from front to back on curb side of bus with passenger air only*

Observation B2: The direction of air flow from front to back on the bus is measurable with an anemometer, as shown in Figure 3-7. Fog positioned rear of the barrier approaches the barrier at low pressures forward and is maintained or sent rearward near the openings on a temporary barrier that is implemented on a bus equipped with HVAC rear exhaust, as seen in Figure 3-8.

Figure 3-7 *Bus A, anemometer demonstration while bus idling with driver defrost and passenger air both on high with driver window and roof hatches closed*

Figure 3-8 *Bus A, air shearing fog on back side while bus idling with driver defrost on high with driver window and roof hatches closed*

C. Identify Methods to Reduce Air Flow from Back to Front

Observation C1: Roof hatches located forward of the axle and next to the bus operator workstation tend to pull air out, which can lead to increased bus operator exposure from air moving from the rear to the front. This is presumably because the hatch is near the leading top edge of the roof, which at high velocities will overcome pressures inside the bus, as demonstrated in Figure 3-9.

Figure 3-9 *Bus A, open front hatch next to bus operator workstation*

Observation C2: When the driver window is open, the pressure inside the front of the bus is induced to be negative due to the Venturi effect and air is pulled from the rear roof hatch forward. This phenomenon was observed even when a temporary barrier was installed to assist in balancing air pressure across the front and rear of a bus equipped with passenger HVAC rear exhaust. Figure 3-10 demonstrates how a telltale string mounted on the front edge of the rear roof hatch is being pulled forward by air flow coming in the roof hatch due to a pressure difference created by the driver window being open.

Figure 3-10 *Bus A, driver window open with hatches open and bus moving at 25 mph; telltales blowing forward due to driver window open*

Observation C3: When the driver window is open, the air is pulled primarily out of the bus to varying degrees based on the bus make and body configuration. Occasionally, during a turning maneuver or when a gust of wind blows against the street side of the bus, the air may briefly enter the driver window, blowing the telltales toward the bus operator. Otherwise, the telltales attached to the bus operator window remain still or are pulled out of the driver window as seen in Figure 3-11.

Figure 3-11 *Bus B, driver window open and hatches closed, telltales pulled out of window*

Observation C4: The booster fan above the bus operator workstation is designed to assist in cooling and heating the bus operator by accelerating the air flow from the back of the bus. However, this feature increases the bus operator's exposure to air from the back of the bus. This was clearly observed while bus C was idling at 0 mph and only the driver defrost air was on, including the booster fan. It is worth noting that the driver window was also open. The fog machine was positioned in the back of the bus and the passenger air was off. However, as seen in Figure 3-12, fog was pulled forward above the bus operator workstation, without any assistance from the passenger air fans, through the overhead ducts in the passenger area.

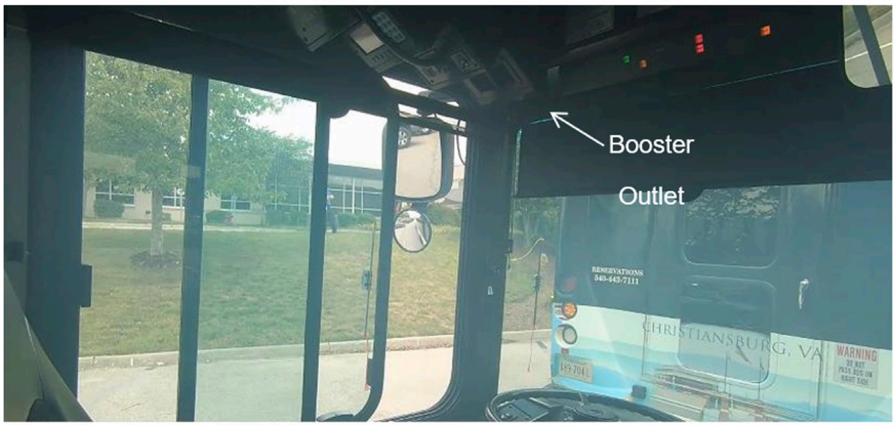


Figure 3-12 *Bus C, fog being pulled forward above bus operator workstation with booster fan active*

This observation emphasizes the point discussed in the air speed velocity measures about local filtering of the air supplied to the bus operator workstation. The booster fan was designed in buses with rear HVAC exhaust to pull more heated/cooled air to the bus operators to increase thermal comfort. In fact, the booster fan is strong enough to pull air from the rear of the bus into the front of the bus without assistance from the passenger HVAC system. Therefore, the booster fan serves a useful function to increase thermal comfort, but it may also increase exposure for bus operators at the same time. Local filtering in the channels that run above the passenger seats and along the length of the bus would support both thermal comfort and reduced exposure.

Temperature Reference Measures During Air Flow Observations

During the air flow testing trials on the test track, outdoor ambient temperatures were recorded approximately every 5–10 minutes using local weather center reports at intervals of every three trials. Additionally, reference interior measures were collected using thermocouples that were located in four places throughout the bus. Table 3-5 lists the range of exterior and interior bus reference temperatures collected during testing. The A/C was inactive during all air flow testing to provide consistent control of the passenger HVAC fan speed on high during all trials among the varying combinations of HVAC, vehicle speeds, and exterior openings. Therefore, temperatures tended to follow outside temperatures. It is also important to note that the windows of buses A and B were covered with black plastic to reduce glare and control backlighting, which may have acted as a radiator for sunlight and artificially elevated the temperatures inside buses A and B.

Almost all trials within each bus and barrier configuration were run within the same day. Baseline trials, without a temporary barrier, were run on separate days than trials with a temporary barrier installed on buses A and B. Trials moved rapidly in 5- and 15-minute incremental successions between variations of the air source (driver defrost/passenger/both), driver window (open/closed), and roof hatches (open/closed) settings. These trials were run consecutively within the same bus speeds. One final set of three trials in bus A at 0 mph had to be completed early on the following day due to bus and bus operator scheduling.

Temperatures and times were collected for reference during bus-front fogging trials at 10 and 25 mph and during bus-rear fogging trials at 0 mph. Outside and interior temperatures were not collected during the repeated trials at 10 and 25 mph with fogging in the rear of the bus. Outside and interior temperatures were not collected for bus C and the BoC bus.

The outside temperatures tended to rise steadily as trials progressed each day and within the same bus. The interior temperatures rose along with the rise in outdoor temperatures. Between sets of trials, the doors of each bus were opened occasionally to allow the bus operator and experimenters to take a break or to allow the fogging machine to be moved from front to back. During these breaks, the interior temperatures occasionally dropped as they balanced with outside temperatures, but also returned to original levels after the doors were closed and trials continued. The weather on testing days ranged from sunny to partly cloudy to mostly cloudy. During one day of testing on bus A (July 21), the outside temperatures dropped in the afternoon from 90 °F at 1:30 pm to 76 °F at 2:45 pm. The interior bus temperatures dropped and then returned to the previous levels over time.

No pattern of interior bus temperatures is apparent between trials. As the A/C was shut off during all test trials to control bus fan speed, the individual performance of each bus HVAC system's cooling cannot be determined from the air flow temperature measures. Temperatures between the buses appear to follow the change in temperatures outside the buses, although they were likely somewhat elevated due to the radiative impact of sunlight. No pattern was obvious from the interior temperatures collected across the four locations on buses A and B or between the baseline and temporary barrier trials. Observations of the maximum interior temperatures measured at each of the four locations on the buses suggest that the temperatures with the temporary barrier installed were similar to or below the measures without the barrier. However, it was important to observe the maximum outside temperatures on each day of testing. The maximum outside temperatures were similar on bus A during baseline (91 °F) and temporary barrier (90 °F) trial days, but the maximum outside temperatures varied on bus B during baseline (86 °F) and temporary barrier (82 °F) trial days and with temporary modified barrier (77 °F) trial days.

Table 3-5 *Bus and Barrier Air Flow Fogging Test Schedule, Outside Temperatures, and Bus Interior Thermocouple Temperatures—T1 – Behind Driver Seat, T2 – Modesty Panel Forward of Barrier, T3 – Seat Rearward of Barrier, T4 – Upper Seating Area*

Bus	Barrier	Date	Time	Outside Temp. (°F)	Bus Interior Temperature Range (°F)							
					T1		T2		T3		T4	
				Min–Max	Min	Max	Min	Max	Min	Max	Min	Max
A	Baseline	7/20/2020	2:30–5:15 pm	89–91	74.9	96.5	71.3	93.3	72.1	94.4	73.1	94.4
A	Barrier	7/21/2020	1:15–3:00 pm	76–90	89.6	92.8	80.2	93.3	77.3	93.4	82.3	91.9
B	Baseline	7/16/2020	11:00 am–2:00 pm	80–86	81.5	98.1	76.7	95.9	76.4	96.4	77.6	99.0
B	Barrier	7/17/2020	8:45 am–12:00 noon	73–82	77.6	95.4	74.1	92.3	72.8	92.9	70.8	95.6
B	Modified Barrier	8/13/2020	3:45–5:30 pm	75–77	80.8	82.5	77.5	83.0	79.9	85.9	81.1	87.6
C	Baseline	8/5/2020	1:00–3:00 pm	80–81	-	-	-	-	-	-	-	-
BoC	Baseline	8/5/2020	4:15–4:45 pm	79	-	-	-	-	-	-	-	-

Informal Cooldown Temperature Measures

The informal 10-minute cooldown temperatures for each bus and temporary barrier configuration are provided in Table 3-6. These informal measures were collected soon after activating the A/C after the air flow measures were completed on each bus while idling at 0 mph. The temperatures of the outside ambient temperatures are provided. The initial and final temperatures after 10 minutes are provided. The temperature differences, labeled "Baseline Minus Barrier Reduction," between the bus baseline and barrier installation are listed at the bottom of each grouping of bus temperatures.

Table 3-6 *Informal (10-Minute) Cooldown Temperatures without and with Barrier for Buses A and B*

Bus HVAC	Temperature Descriptions	Front (°F)	Barrier F. (°F)	Barrier R. (°F)	Rear (°F)
Bus A, Rear Exhaust	Outside Ambient, Baseline	90, cloudy			
	Interior Initial Temp., Baseline (T_1)	102.7	101.9	98.7	99.3
	Interior Final Temp., Baseline (T_2)	97.3	88.4	89.7	91.8
	Temp Difference, $\Delta T_{Base1} = (T_1 - T_2)$	5.4	13.5	9.0	7.5
	Outside Ambient, Barrier	81, cloudy			
	Interior Initial Temp., Barrier (T_3)	93.5	91.8	89.4	89.7
	Interior Final Temp., Barrier (T_4)	87.4	80.2	78.7	82.5
	Temp Difference, $\Delta T_{Bar1} = (T_3 - T_4)$	6.1	11.6	10.7	7.2
	$\Delta T_{Final\ Bus\ A} = (\Delta T_{Base1} - \Delta T_{Bar1})$	-0.7	1.9	-1.7	0.3
Bus B, Roof Exhaust	Outside Ambient, Baseline	84, partly cloudy			
	Interior Initial Temp., Baseline (T_5)	98.8	90.1	89.6	92.5
	Interior Final Temp., Baseline (T_6)	83.5	79.3	76.6	74.9
	Temp Difference, $\Delta T_{Base2} = (T_5 - T_6)$	15.3	10.8	13	17.6
	Outside Ambient, Barrier	86, cloudy			
	Interior Initial Temp., Barrier (T_7)	86.8	90.3	90	90.5
	Interior Final Temp., Barrier (T_8)	83.7	85.7	82.4	81.8
	Temp Difference, $\Delta T_{Bar2} = (T_7 - T_8)$	3.1	4.6	7.6	8.7
	$\Delta T_{Final\ Bus\ B} = (\Delta T_{Base2} - \Delta T_{Bar2})$	12.2	6.2	5.4	8.9

The differences between the reduction in temperatures over 10 minutes in the baseline trials versus the temporary barrier trials on each bus are demonstrated in Figure 3-13. Negative temperature differences demonstrate that the final temperature on the temporary barrier configuration reduced more than the baseline. Positive temperature differences demonstrate that the final temperature on the temporary barrier reduced less than the baseline. Negative differences resulted on bus A for the temperature in the front near the bus operator workstation and at the rear of the barrier. The other two measurement locations on bus A did not reduce as much, although the final temperatures were only slightly higher with the temporary barrier than the baseline. However, on bus B the temperatures across all measurement locations were positive, demonstrating that the final temperature for the temporary barrier configuration did not decrease as much as the baseline configuration.

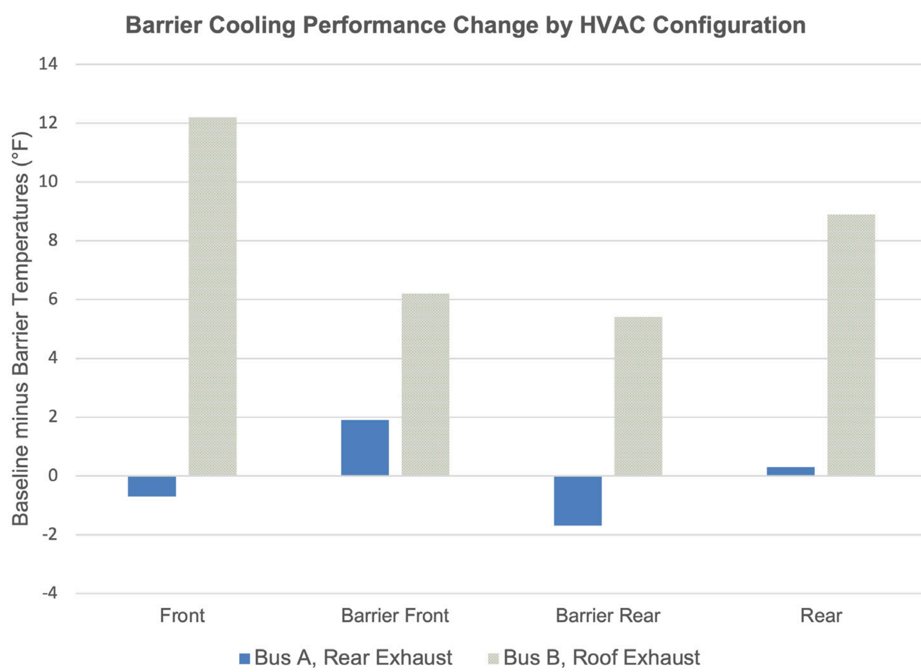


Figure 3-13 *Temperature (10-min.) reduction difference between baseline and temporary barrier split by measurement location in buses A and B HVAC configurations*

Section 4 Stakeholder Interactions

Due to the nature of this research, which was conceived and completed during the first year of the COVID-19 pandemic and the need to respond immediately to feedback from public health and transit agencies, the research team sought many opportunities to meet with representatives from public transit stakeholders throughout the project.

VTTI supported the Center for Urban Transportation Research (CUTR) online progress meetings with the FTA Standards Development Program during June, July, August, and October 2020 and February and August 2021. During these Web meetings, VTTI described the study methodology, observations, results, and recommendations, as well as lessons learned through testing on multiple transit bus HVAC configurations.

VTTI also supported Web meetings with CUTR's Standards Working Group progress meetings in August and November 2020, during which VTTI research personnel identified the key research questions and played sample videos of the fogging air flow data collection, which provided the evidence that VTTI used to analyze and draw conclusions.

VTTI was asked to share preliminary findings with the American Public Transportation Association (APTA) after highlighting the study during a public webinar held in August 2020, at which VTTI participated to discuss engineering controls for mass transit. VTTI also presented during the Joint Transportation Research Board/APTA 2020 Mid-Year Transit Safety and Security Meeting in November 2020. VTTI also presented during the APTA Monthly Safety Spotlight in January 2021 and at the Transportation Research Board Annual Meeting 2021 to AP080, Standing Committee on Transit Safety and Security in January 2021.

VTTI shared preliminary findings with the transit agencies that supported the testing as results were observed. In September 2020, VTTI shared additional preliminary findings with these organizations. VTTI received a request from Sound Transit to provide further details of the study procedures and to discuss other air ventilation testing methods that their transit agency was using to measure air exchange rates. VTTI shared the testing procedures and preliminary findings with their Industrial Hygiene Program Manager and an operations director during a Web meeting held September 2020. Additionally, VTTI received a request from New York City Transit to provide more information on the study in September 2020.

VTTI produced technical memos on the study to share with stakeholders at important stages in the project—for example, after completing on-road jet testing, before initiating VSR track fog testing, and after completing all vehicle testing. VTTI also developed a two-page summary of the research and recommendations, provided in Appendix E and available at https://www.vtti.vt.edu/PDFs/Transit%20Bus%20Engineering%20Controls.pdf.

Section 5

Conclusions

VTTI performed this research project under contract with CUTR at the University of South Florida in support of FTA's Standards Development Program. The purposes of this project were to (1) demonstrate the production of a durable physical temporary barrier between the front and rear passenger compartment of a transit bus to reduce the exposure risk to COVID-19 for the operator and passengers; (2) perform an air flow test of the temporary barrier; and (3) share the results to maximize the positive impact to the public transportation system throughout the U.S. The VTTI research team completed the objectives, and the outcomes of the research are summarized in the following sections.

Transit Bus Airflow Findings for Transit Agencies

The results of the observations and measurements are organized in Table 5-1 according to the air flow objectives of the study. These settings may be considered by transit bus agencies for implementation depending on their bus configuration as equipped.

Table 5-1 *Air Flow Management Objectives and Configuration Settings*

Objectives	Bus/HVAC Configuration Considerations	Optimal Bus/HVAC Settings
Maximize air dilution for bus operators and passengers	Windshield defrost vent fresh/recirculate	If equipped, set defrost vent to full fresh and defrost fan to high.
	Windows in passenger compartment	If equipped, open passenger windows depending on outdoor weather/temperature.
	Front roof hatch	If equipped at or rear of front axle, open front roof hatch depending on outdoor weather/temperature.
	Rear roof hatch	Open rear roof hatch depending on outdoor weather/temperature.
	Bus operator workstation driver window	Close driver window.
Pressure barrier near bus operator for airflow management	Rear HVAC system; two-door bus entry; rear-mounted touchless fare system	Install temporary barrier near the bus front (i.e., behind ADA section) with minimum gaps (i.e., approx. 1 in.) to floor, walls, and ceiling to minimize cabin air mixture with bus operator.
	Bus operator workstation driver window	Close driver window to maintain positive pressure around the temporary barrier.
Reduce air flow from bus rear to front	Bus operator workstation driver window	Close driver window to reduce cabin air mixture (i.e., rear-to-front flow) during vehicle motion.
	Front roof hatch	If equipped near bus operator workstation, close front roof hatch to reduce cabin air mixture (i.e., rear-to-front flow) during vehicle motion.
Avoid impacting HVAC cabin temperature management	Bus–rear HVAC system	If equipped (based on limited outdoor cooldown temperature testing), the temporary barrier did not impact cabin temperature management.
	Bus–mid HVAC roof-mounted system	If equipped (based on limited outdoor cooldown temperature testing), the temporary barrier impacted cabin temperature management.

Testing Limitations and Lessons

The following are lessons on methodology learned during testing:

- The track testing was a cost- and time-efficient procedure that could provide observational measures of aerodynamic effects on the evaluation of an open-air system intended to reduce viral concentration.
- Chamber testing is appropriate for closed/semi-closed system measurements of temperature and humidity.
- Heated oil fogging was effective to cover a large-volume bus cabin system with onboard operators during dynamic testing—compared to the carbon dioxide fogging application. Liquid moisture instrumentation should be considered in future methodologies.
- Vehicles were not mechanically altered to separate the heat or A/C from the HVAC system, so fan-only testing was performed. Impacts to HVAC system pressures are unknown when heat and A/C are active.
- The visualization procedure for fogging air flow could be altered to delay every combination (defrost, HVAC, window, hatch) until the bus reaches a fresh (unsaturated) state, but this change to procedure may significantly increase time and cost resources.

Practices to Reduce Exposure

The following general practices to reduce exposure to COVID-19 on different transit bus configurations should be considered:

- Apply principles of gravity (physical distance) and dilution (fresh air) along with organized airflow to reduce COVID-19 exposure for bus operators and passengers.
- Close driver window.
- Open rear roof hatch to increase front-to-rear flow and fresh air mixing; close front roof hatch, if located near the bus operator workstation; open front roof hatch, if located rearward of the front axle.
- When equipped, set driver heater/defroster on maximum (100%) fresh with the fan on high.
- Filter (HEPA) or close the operator workstation air grille connected to the passenger area HVAC system.
- A filtering option allows the bus operator to maintain the heating/cooling benefits.
- For rear-mounted HVAC-return-equipped buses, consider construction and installation of a temporary barrier near the ADA area to organize interior air flow from front to back; best when combined with a rear-door entry touchless fare system.

The bus images in Figure 5-1 illustrate sub-optimal and optimal implementation of temporary engineering controls.

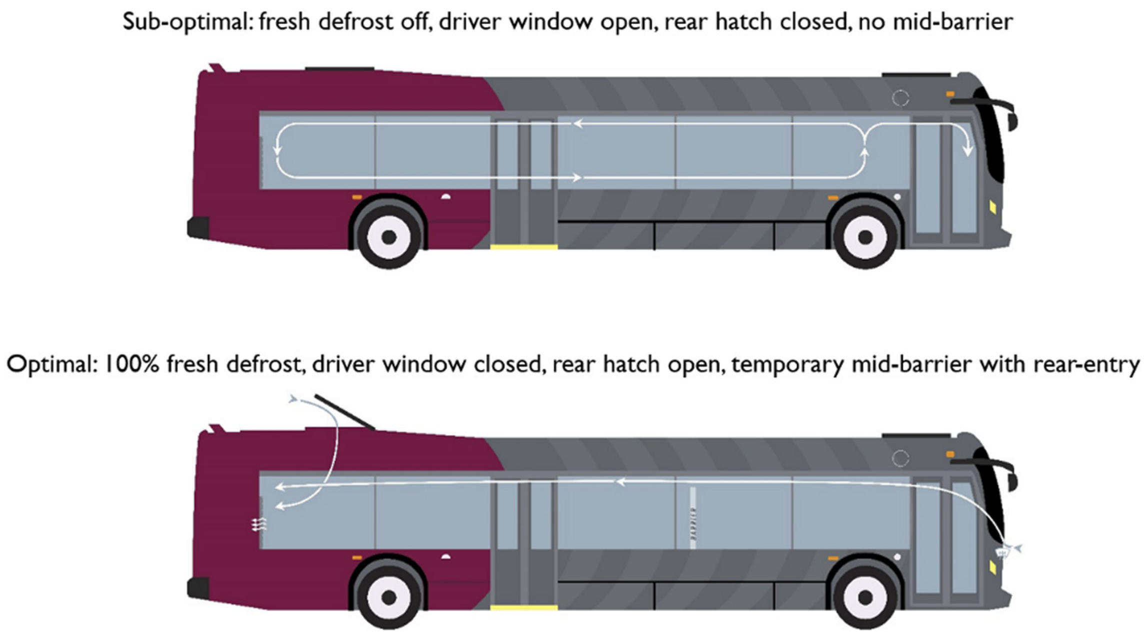


Figure 5-1 *Sub-optimal (top) and optimal (bottom) implementation of transit bus HVAC and exterior openings*

Transit Bus Configuration Designs and Air Flow

The research team discovered important design elements of transit buses from interactions with stakeholders and through testing that should be considered in future implementation of temporary and permanent controls to reduce the risk of internal viral concentrations.

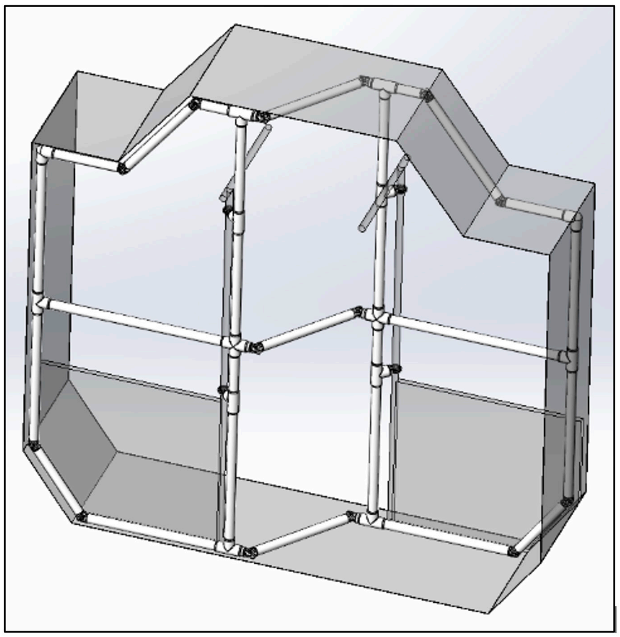
- Transit buses are increasingly tightly controlled and sealed closed air cabin systems to reduce external environmental pollution. This can lead to low cycle times for internal air, especially on older transit bus models.
- Closed HVAC systems with steady forced air into the bus from mixed inlets tend to have positive pressure, which forces air out of the bus in leaks and openings unless overcome by aerodynamic factors while in motion (e.g., Venturi effect).
- Closed HVAC systems that primarily recycle internal air tend to have negative pressure, which can cause external air to be pulled in through leaks or openings.
- Temporary solutions can be applied to increase the percentage of outside air circulated by opening the cabin air systems. When opening the system, external aerodynamics need to be considered to reduce exposure to bus operators.

Appendix A

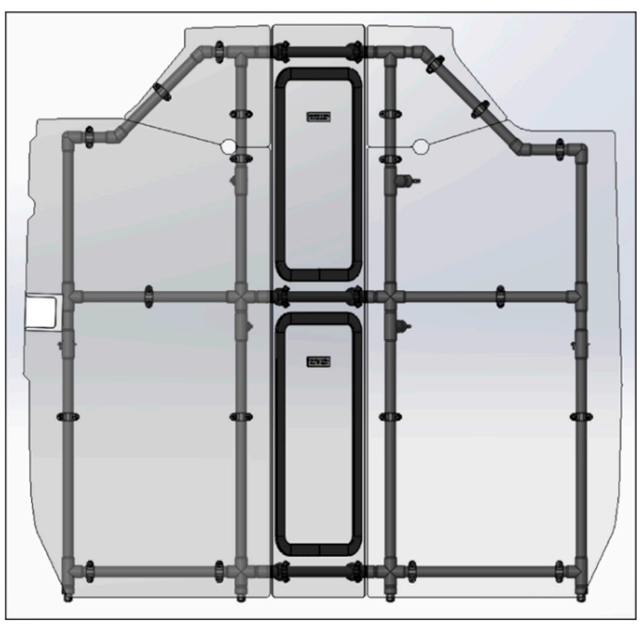
Transit Temporary Barrier CAD Models

Universal CAD model files are available upon request in Solidworks and STEP file formats. Requests may be sent to inquiries@vtti.vt.edu.

Early Prototype Model



Final Prototype Model



Appendix B

FMVSS Considerations

A temporary barrier was developed to reduce the exposure of transit bus operators to passengers who may be infected with COVID-19. The barrier design was intended for temporary use to enhance safety during the COVID-19 pandemic. The temporary barrier was designed to mount to existing transit bus stanchions and by resting on the floor. It was also intended to be mounted without body fasteners and without causing permanent damage to the interior body of the bus. The intention was for the temporary barrier to be removed when the transit agency and operating officials identify that the risk of COVID-19 transmission to transit bus operators has been mitigated or eliminated through other controls or public methods.

The concept temporary barrier was designed to:

- Physically limit access of passengers near bus operator when boarding through rear door.
- Be durable enough to last approximately one year (except for abuse or vandalism).
- Enhance unidirectional flow of bus air ventilation for bus configurations with rear-mounted passenger HVAC exhaust from front to back (i.e., away from bus operator), improving safety for operators and improving aerosol extraction for passengers.

The temporary barrier design also included break-away features to allow the upper and lower center panels to be kicked or pressed for removal if needed for evacuation. It should be noted that the existing emergency exits located in the front and rear of each bus did not interface with the temporary barrier, and this design feature came with an abundance of caution. Each of the two upper and lower center panels had a surface area that meets the minimum APTA guidelines for roof ventilator/ emergency exit area, which is 425 square in. (5.4.8.5 Roof Ventilators), although the panels are rectangular due to the width of the aisles. The force required to remove the center panels was designed to meet the APTA guidelines for emergency door operation, which is a force of no more than 25 lbs (5.4.5.3.9 Emergency Operation). A label should be attached to each upper and lower center panel that informs the reader to “Push firmly to remove in case of emergency.” The force can be applied to the front or rear surface to remove each panel. The temporary barrier should be installed to allow access to all emergency exits, including doors, windows, and roof hatches.

Per FMVSS NO. 217, access to a window that serves as an emergency exit should ensure that at least 3,458 square cm of that window are accessible and that the opening is large enough to admit unobstructed passage, keeping a major axis horizontal at all times, of an ellipsoid generated by rotating about its minor axis an ellipse having a major axis of 50 cm and a minor axis of 33 cm. The temporary barrier was also designed to allow access to latches used to open emergency exits. The temporary barrier was designed with a hole (125 x 125 mm) for hand access to reach the emergency window latch, if so equipped on each bus near the temporary barrier.

The temporary barrier was designed for installation rearward of the ADA seating area and behind the front seats or modesty panels to avoid interference with the ADA securement system. Pertaining to FMVSS No. 217 requirements, the temporary barrier was designed to be installed behind the bus operator workstation and to avoid interference with access by the bus operator (i.e., driver) or passengers to bus emergency exits. Pertaining to FMVSS No. 205, the temporary barrier was made of transparent polycarbonate and was not coated with any glazing materials. The design was intended to allow for communication between the bus operator and passengers, as well as to allow observation of the rear door entry by the bus operator with existing interior mirrors. Additionally, regarding FMVSS 111, the temporary barrier was designed to avoid interference with the driver's view to the exterior side and rear mirrors.

Appendix C Parts and Construction Lists

Parts List

McMaster-Carr Part #	Item	Qty
4824T7	Plastic Framing Rail 1-5/8" OD, Black, 10 ft	5
4824T99	Plastic Framing Caster Fitting	8
4824T97	Plastic Framing Cross Fitting	4
4824T98	Plastic Framing Cap Fitting	2
4824T93	Plastic Framing 45 Degree Elbow Fitting	10
4824T88	Plastic Framing 90 Degree Elbow Fitting	2
4824T89	Plastic Framing Tee Fitting	12
18815K51	Clear PVC Primer (8 oz)	1
74605A14	Clear PVC Cement (8 oz)	1
8574K74	Clear Impact-Resistant Polycarbonate (4 'x 8' x3/16")	3
7211A45	Optically Clear Tape, 2" x 27'	2
2236T34	Stackable Clamping Hanger, 1-1/4" ID (to match vertical handrail)	4
90313A104	Washer, 0.203" ID, 1.000" OD (for handrail mount to caster fitting)	4
91831A011	Nylock Nut, 10-24 (for handrail mount to caster fitting)	4
92210A253	Flat Head Screw, 10-24, 2" Long (for handrail mount to caster fitting)	4
3176T34	Vibration Damping U-bolt (to attach panels to framing)	26
94709A516	Rubber-Bonded Washer, 0.434" ID, 1.000" OD (for panels)	52
2615T16	Clamping Hanger, 1-11/16" ID (for framing - privacy screen hand grip)	2
2615T15	Clamping Hanger, 1-3/8" ID (for privacy screen hand grip - framing)	2
95475A626	Threaded Rod, 3/8"-16, 1-1/4" long (to connect clamping hangers)	2
91078A031	Jam Nut, 3/8"-16 (for clamping hangers)	4
9546K51	Polyurethane Bumper, 3/8"-16, 1-1/4" OD, 1-1/4" height (for feet)	4
91205A630	Thread-Locking Screw, 3/8"-16, 1-3/4" long (for feet)	4
91525A136	Washer, 0.406" ID, 1.000" OD (for feet)	4
1566N236	Ultra-Weather-Resistant EPDM Foam Strip, 12" Wide, 1/2" Thick, 12" Long (for emergency window latch access cover)	1
Wefco Rubber 2395	Rubber H-channel for Breakaways (http://www.wefcorubber.com/extrusions_industrial_hchannels.asp) or similar, 96.5" for upper, 106.25" for lower	

Cutlist for Plastic Framing Rail

Generating the following components:

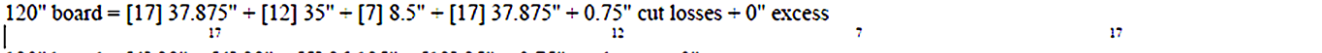
[1] → 2.5" (x8)
[2] → 2.75" (x6)
[3] → 21.25" (x4)
[4] → 29" (x2)
[5] → 26.125" (x2)
[6] → 6.5" (x1)
[7] → 8.5" (x1)
[8] → 18.5" (x1)
[9] → 5" (x1)
[10] → 3.75" (x1)
[11] → 3" (x2)
[12] → 35" (x2)
[13] → 6" (x2)
[14] → 5.875" (x2)
[15] → 24" (x1)
[16] → 22" (x1)
[17] → 37.875" (x2)
[18] → 17" (x2)
[19] → 19" (x2)

The following stock board lengths are available:

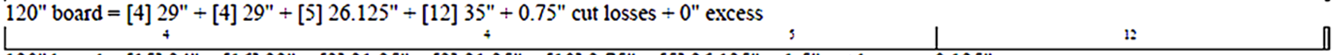
120"

Results:

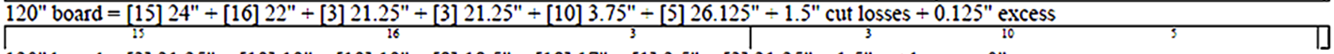
120" board = [17] 37.875" + [12] 35" + [7] 8.5" + [17] 37.875" + 0.75" cut losses + 0" excess



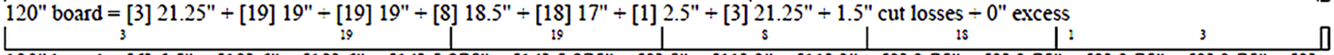
120" board = [4] 29" + [4] 29" + [5] 26.125" + [12] 35" + 0.75" cut losses + 0" excess



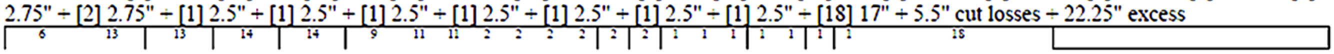
120" board = [15] 24" + [16] 22" + [3] 21.25" + [3] 21.25" + [10] 3.75" + [5] 26.125" + 1.5" cut losses + 0.125" excess



120" board = [3] 21.25" + [19] 19" + [19] 19" + [8] 18.5" + [18] 17" + [1] 2.5" + [3] 21.25" + 1.5" cut losses + 0" excess



120" board = [6] 6.5" + [13] 6" + [13] 6" + [14] 5.875" + [14] 5.875" + [9] 5" + [11] 3" + [11] 3" + [2] 2.75" + [2] 2.75" + [2] 2.75" + [2] 2.75" + [2] 2.75" + [2] 2.75" + [1] 2.5" + [1] 2.5" + [1] 2.5" + [1] 2.5" + [1] 2.5" + [1] 2.5" + [1] 2.5" + [18] 17" + 5.5" cut losses + 22.25" excess



Board Count:

5x 120" (10')

Assembly

Stage	Task	Drawing/Reference File(s)	Hours Est/ Person	No. Persons	Total Hours	Note
Pre-assembly	Cut plastic rail to length	PlasticFramingRailCutlist.pdf	3	1	3	
Pre-assembly	Cut polycarbonate sheets to shape	Panel_Curbside_19XX.DWG, Panel_Streetside_19XX.DWG, Panel_Center_19XX_Breakaway.DWG	3	1	3	Or have waterjet/ laser cut
Pre-assembly	Assemble feet	FootAssembly.DWG	1	1	1	
Pre-assembly	Assemble vertical hand-rail clamps	PipeClampAssembly.DWG	1	1	1	
Pre-assembly	Pre-assemble framing, glue joints labeled "A"	PlasticRailingFittingsAssembly.DWG, AssemblyLengths.DWG	3	1	3	
Pre-assembly	Place U-bolts roughly in position on frame	PlasticRailingFittingsAssembly.DWG	0.5	1	0.5	
Pre-assembly	Cut rubber H-channel to length, attach breakaways to center panel	Panel_Center_19XX_Breakaway.DWG, 96.5" for upper, 106.25" for lower	0.5	1	0.5	
Assembly	Assemble frame in place, glue joints labeled "B," attach hand-rail clamps	PlasticRailingFittingsAssembly.DWG, AssemblyLengths.DWG, PipeClampAssembly.DWG	2	2	4	
Assembly	Attach panels to frame		1	2	2	Be sure to use rubber-bonded washers to protect plastic panels from nuts
Assembly	Seal gaps with clear tape		0.5	2	1	

Appendix D Testing Instrumentation

The instrumentation applied for each type of testing is described below.

Air Jet Telltales

1. Very high bonding (VHB) adhesive tape, painter's tape, ¼-in. dowel rods, fluorescent yellow and pink nylon string, extender brackets to elevate above surfaces, sharp knife or scissors to feather the nylon string
2. Specifications:
    a. Painter's tape: 3M - 2090 Scotch-Blue Painter's Tape, 1 in.
    b. ¼-in. dowel rods: Fiberglass reinforced plastic (FRP) rod, ¼-in. diameter, cut to 1 ft long
    c. Fluorescent yellow and pink nylon mason line string (tied to dowel rod using a clove hitch knot and glued in place using Loctite Instant-Bond Adhesive 416), braided nylon, size 18 – 6-in. core
    d. Extender brackets to elevate above surfaces: 3D-printed polylactic acid, thermoplastic polyester (PLA) to offset the center of the rod 1 from the surface
3. Mounting locations: driver's window; street-side A-pillar; driver defrost ducts; passenger air driver-workstation ducts; windshield high and low; front entrance ducts; passenger air ducts; passenger floor and roof/rear exhaust
4. Telltale locations that would best demonstrate the airflow were selected. Nylon string lengths were determined based on the air flow direction and force of air. All strings started at 8-in. in length and were trimmed to 6 or 3 in. as needed, dependent on location per bus. The ends of the strings were also frayed to better capture airflow.
5. GoPro Cameras
    a. GoPro HERO6 (x2)
        i. Specifications: full color, GPS, high definition, image stabilizing, night mode, touch screen, waterproof, widescreen video, 12 MP, 4K, 1080p, 720 p, 128 GB micro-SD card
    b. Recording specifications: 1080p, 30 fps, normal angle

Interior Bus Temperature

1. Digital thermometer, thermocouples, painter's tape for adhering thermocouple wires to bus interior
2. Mounting and temperature collection locations: behind driver seat, on front of street-side modesty panel by ADA section (forward of temporary

barrier), on back of street-side passenger seat (rearward of temporary barrier), on side of street-side passenger seat in elevated seating area. Thermocouples were placed so no other objects or persons would affect the ambient temperature near them. Painter's tape was used for adhering thermocouple wires to bus interior.

3. Digital thermometer: Gain Express – 4 channel K type thermometer
   a. Specifications:
      i. Temperature range: -200 to 1370 °C / -328 to 2498 °F
      ii. Temperature resolution: 0.1 °C/°F
      iii. Temperature accuracy: under 18~28C ambient temp. ± (0.3% rdg +1 °C)
4. Thermocouples: K type 0-400 °C temperature sensor thermocouple probe copper wires at 4 M (1 ea), 5 M (2 ea), and 20 M (1 ea)
   a. Specifications:
      i. Material: plastic and metal
      ii. Color: white and orange
      iii. Temperature range: 0 to 400 °C; accuracy: ±2.5%/0.75%
      iv. Pin spacing: 5 mm/0.2"

Air Speeds

1. Handheld digital anemometer: BTMETER - BT-846A, Pro HVAC anemometer
   i. Specifications:
      1. Wind speed range: 0.001~100 mph (accuracy: ±3% ±0.2 reading), resolution: 0.001
      2. Air temperature range: 32.0-113.0 ^{0}F (0~45 ^{0}C), resolution 0.1
      3. Speed units: m/s, km/h, ft/min, knots, mph

Air Flow Tracing

1. 0.3-mil black plastic was installed with painter's tape over all windows except for the forward windshield, driver's window, and front entrance windows.
2. Fogging machine: JDR Portable 400W Smoke Machine
3. Fogger fluid: FogWorx Fog Juice
   a. Product information: medium density – all organic ingredients and works in all fog machines designed for water-based fluid. Specially formulated fog machine fluid with premium pharmaceutical grade chemicals, to produce a medium density fog with great hang time and dispersion.

4. Two GoPro digital video recorders were handheld during testing and a third GoPro video recorder was mounted on a curb-side window in front of the barrier to capture continuous airflow near the barrier.
5. GoPro cameras
   a. GoPro HERO
      i. Specifications: full color, high definition, night mode, waterproof, widescreen video, 5 MP, 1080p, 720p, wide-angle lens, 32 GB micro-SD card
   b. GoPro HERO6 (x2)
      i. Specifications: full color, GPS, high definition, image stabilizing, night mode, touch screen, waterproof, widescreen video, 12 MP, 4K, 1080p, 720 p, 128 GB micro-SD card
   c. Recording specifications: 1080p, 30 fps, normal field of view angle

Appendix E

Temporary Transit Bus Engineering Controls to Reduce COVID-19 Exposure

TEMPORARY TRANSIT BUS ENGINEERING CONTROLS TO REDUCE COVID-19 EXPOSURE

NEED

Transit buses provide essential transportation service. Transit bus operators may be at risk of exposure to passengers with COVID-19 at close interactions for short periods of time and distant interactions over longer periods of time. Viral exposure risks include lack of physical distance during front door entry; lack of physical distance while supporting passengers (e.g., ADA securement); and potential air exchange hazard.

SHEN, Y. ET AL. (2020) JAMA INTERNAL MEDICINE | CDC (OCTOBER 5, 2020) SCIENTIFIC BRIEF ON AIRBORNE TRANSMISSION

VIRGINIA TECH TRANSPORTATION INSTITUTE
VIRGINIA TECH.

INVESTIGATION PURPOSE

1. Reduce bus operators' exposure to the presence of COVID-19 in airborne droplets and particles.
2. Maximize fresh air for passengers who occupy buses for shorter periods of time than bus operators.
3. Determine feasibility of a temporary barrier to organize air flow and pressure in a transit bus.

ENGINEERING CONTROL SOLUTION

Three barrier designs were considered, including one near the bus operator workstation and two in the passenger compartment. A barrier design was developed prior to testing to meet the air quality objectives: (a) maximize fresh air for dilution, (b) produce a pressure differential inside the bus to organize air flow, (c) identify other methods to reduce exposure for bus operators.

HIERARCHY OF CONTROLS

To reduce risks to workers, the range of controls used in workplaces include elimination, engineering, administrative, and personal-protective equipment (PPE).

Other than elimination, engineering controls are the most effective risk reducers. According to OSHA, "In workplaces where appropriate, these types of controls reduce exposure to hazards without relying on worker behavior."
(GUIDANCE ON PREPARING WORKPLACES FOR COVID-19 (2020) OSHA 3990-03)

This investigation, performed by the Virginia Tech Transportation Institute (VTTI), focused on applying a temporary barrier as a physical and ventilation engineering control to reduce bus operator exposure to COVID-19. The study also sought to identify other bus features that may provide ventilation benefits.

NO VENTILATION CONTROLS

OPTIMAL VENTILATION CONTROLS

AIR FLOW OBSERVATIONS

REAR-MOUNTED HVAC RETURN

Organized flow front-to-rear was achieved with the temporary barrier when the front roof hatch and driver window were closed.

If the bus is equipped with a fresh/recirculate option for the driver heater/defroster, fresh air helps resist rear air flowing toward the bus operator.

A driver HVAC booster fan blows air from the passenger area into the bus operator workstation.

Interior cooling temperatures were largely unaffected by installation of the temporary barrier.

ROOF HATCHES AND DRIVER WINDOW

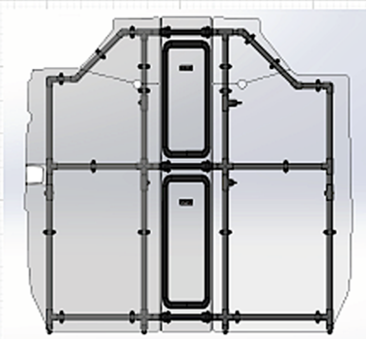
Driver window open drew air out and towards the driver, overcoming all other air flow effects.

Rear roof hatch open drew air into the bus and forward towards the bus operator when the driver window was open.

Rear roof hatch open drew air into the bus and rearward on a rear-mounted HVAC return equipped bus when the driver window was closed and the passenger air was active.

Front roof hatch open near bus operator workstation drew air out and towards the driver, overcoming all other air flow effects of driver HVAC, passenger HVAC, rear hatch, and temporary barrier.

Front roof hatch open rearward of front axle drew air into the bus and away from driver. This configuration was only evaluated without the temporary barrier.



TEMPORARY BARRIER DESIGN FEATURES

Physically limits passenger access near bus operators when combined with rear-door entry, and durable enough to last approximately one year (barring abuse or vandalism).

Supports interior bus ventilation flow from front to back on buses equipped with rear-mounted passenger HVAC air returns, improving safety for operators and passengers by reducing exposure and increasing airborne particle extraction.

Has no moving parts and does not interfere with bus operator workstation access or visibility. Gaps between the barrier and the bus ceiling (1 and 3 inches) provide for organized flow.

Design can be modified to fit many bus make/model configurations that are equipped with rear doors. Considers national APTA and FMVSS standards. Barrier features support emergency egress.

THE FOLLOWING GUIDANCE IS BASED ON THE VIEWS OF VTTI AND NOT THE FEDERAL TRANSIT ADMINISTRATION.

COVID-19 EXPOSURE REDUCTION FOR BUS OPERATORS AND PASSENGERS

Apply principles of gravity (physical distance) and dilution (fresh air) with organized air-flow to reduce exposure.

- Close driver window.
- Open rear roof hatch to increase front to rear flow and fresh air mixing; close front roof hatch if located near bus operator workstation; open front roof hatch if located rearward of front axle.
- When equipped, set driver heater/defroster on max (100%) fresh with the fan on high.
- Filter (HEPA) or close operator workstation air grille connected to the passenger area HVAC system.
- Filtering option allows the bus operator to maintain the heating/cooling benefits.
- For rear-mounted HVAC return equipped buses, consider construction and installation of temporary barrier near ADA area to organize interior air flow from front to back. Best when combined with rear-door entry touchless fare system.

FOR QUESTIONS & AVAILABLE RESOURCES:

3D & 2D CAD Models | Parts & Cut Lists | Assembly Description | Implementation Documents

Contact: **akrum@vtti.vt.edu**

U.S. Department of Transportation
Federal Transit Administration

CUTR CENTER FOR URBAN TRANSPORTATION RESEARCH

BT Blacksburg TRANSIT

Valley Metro Roanoke, Virginia

Acronyms and Abbreviations

ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ATU	Amalgamated Transit Union
BoC	Body on Chassis
BT	Blacksburg Transit, Blacksburg VA
CAD	Computer-Aided Design
CDC	Centers for Disease Control and Prevention
COVID-19	Coronavirus Disease 2019
CUTR	Center for Urban Transportation Research
FMVSS	Federal Motor Vehicle Safety Standards
FRP	Fiberglass Reinforced Plastic
FTA	Federal Transit Administration
HVAC	Heating, Ventilation, and Air Conditioning
MERV	Minimum Efficiency Reporting Value
PLA	Polylactic acid, thermoplastic polyester
PPE	Personal Protective Equipment
USF	University of South Florida
VHB	Very High Bonding
VM	Valley Metro, Roanoke VA
VSR	Virginia Smart Roads
VTTI	Virginia Tech Transportation Institute

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Federal Transit Administration

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https://www.transit.dot.gov/about/research-innovation