AMERICAN PUBLIC TRANSPORTATION ASSOCIATION
WHITE PAPER
1300 I Street, NW, Suite 1200 East, Washington, DC 20006

APTA Mobility Recovery and Restoration Task Force
Published: Sept. 2, 2020

Transit Leadership in the Post-COVID-19 Mobility Landscape

Part One: Measures to Promote Safe Mobility

Abstract: Professional communities of transit designers, architects and engineers have a profound responsibility to ensure that proper design measures are implemented to promote the health and safety of transit riders and employees in a post-COVID-19 world. The pandemic has created an opportunity to influence physical components of transit facilities and vehicles to make them less conducive to the spread of pathogens. This paper describes architectural, ventilation and air sanitization interventions that advance the safety of transit riders and employees. Part Two of this series discusses behavior interventions and branding.

Keywords: aerosols, air exchange rate, airborne, architectural measures, carbon dioxide (CO_2), cleaning, coatings, COVID-19, disinfection, distancing, droplets, escalators, fresh air supply, HVAC, hydrogen peroxide (H_2O_2), ionization, pandemic, pathogen spread, public safety purification, sanitization, seating, stations, surfaces, touch-free, transit agencies, transit facilities, transmission, UV light, UVC light, ventilation, ventilation measures, virus

Summary: For COVID-19, or pathogens of a similar nature, there is a risk of transmission among transit riders, especially when confined in enclosed spaces such as stations, waiting areas, platforms, trains and buses. Various architectural and ventilation measures, including air sanitization, could be an effective way of neutralizing viral pathogens and arresting the spread of the disease. The measures identified in this white paper represent a compendium of potential actions intended to provide transit agencies with a range of solutions. Some of these measures are already in use, nationally or internationally; and new measures and solutions have been identified from their historically known effectiveness elsewhere. Each of these measures has been evaluated for ease of application, effectiveness, cost and equity.

Scope and purpose: This paper is designed to help transit agencies arrive at practical and readily deployable technical solutions (architectural, ventilation and air quality) to facilitate the efficient restoration of transit services in a pandemic-transformed society; to establish a guide for a design approach to influence and promote future safe practices in transit facilities and vehicles; and to apply equity principles through the application of technical solutions.

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Introduction and participants

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Under the direction of Kimberly Slaughter, senior national practice consultant at HNTB, the individuals listed above formed a workgroup to capture the research and thought leadership findings that will support the restoration of services within our industry. We guided the work through the application of Adaptive Leadership Principles [1]. This means the work was conducted to separate technical solutions from behavioral solutions, and an emphasis was placed on building collaborative partnerships and focused messaging. We defined technical challenges as those that could be addressed through know-how and adaptive challenges as those that require people learning new behaviors. We worked with the understanding that adaptability is the essential ingredient for surviving and thriving as we move through and beyond the COVID-19 pandemic.

The work was built on the following goal: to create a post COVID-19 transit environment that is safe and healthy to the riding public. To achieve this, we provided these problem statements for each group to address:

- **Technical Solutions Group (Part One):** How do we use emerging data and research to make impacts on our services beyond the next 12 months?
- **Workforce and Ridership Behaviors Group (<u>Part Two</u>):** As leaders, how do we balance the need for technical solutions while addressing the emotional responses of our patrons and workforce?
- **Key Messaging and Branding Group (<u>Part Two</u>):** How do we create a culture of trust within the industry?

This paper is designed around the three areas identified above: technical solutions, workforce and ridership behaviors, and key messaging and branding. Applying the concepts of adaptive leadership, the group addressed the problem statements by exploring practical ideas and then gaining perspective on the application of these potential solutions. Heifetz and Linsky, authors of "Leadership on the Line" [1], describe this approach as moving from the dance floor to the balcony. It has also been called "contemplation in action." It is about stepping back to learn what is really happening within your environment.

We felt that this methodology was particularly important during this time of uncertainty. It is easy to get lost in the fog of the pandemic, and it is not always instinctual to be reflective during a crisis. The subgroup invited students from the current Leadership APTA class to assist in the process of moving from the dance floor to the balcony. Seventeen of these emerging senior and executive leaders from across the country volunteered to help and were assigned to support the leads within each of the three areas. By engaging these experienced stakeholders from within the industry, the Research and Thought Leadership Group was able to gain diverse perspectives to assist in guiding the outcome of the work. Leadership APTA participants aided with research and evaluation. The value of their diverse perspectives was key to the comprehensive findings of this paper.

That approach was complemented by the contributions of Flora Castillo, president of Pivot Strategies. Castillo challenged the group to consider the key partnerships that will need to be formed to execute the work identified in the plan. In particular, she assisted in identifying nontraditional partners, such as providers of public health services.

One of the essential elements of this group's work has been to be intentional about inclusion and equity for any of the recommended work products. We exercised our intention by using the Rapid Equity Assessment designed at Los Angeles Metro, which is presented in the appendix of Part Two. While this tool was not an extensive assessment, it set the foundation of the work to be grounded in equity principles. Further assessments of equity impacts will need to continue during any execution of the findings.

Our professionals have used the most relevant science to recommend technical solutions. The behavioral work recognizes that it will take people adapting their practices to make the technical solutions effective and that communication with key messaging is the secret sauce to success. Our ability to make long-term change is embedded in building strong partnerships and using strategic messaging. These three prongs will bring an inclusive approach to restoring a transit environment that is safe and healthy to the riding public.

The sub-groups included the following members from the Leadership APTA Class 2020-21:

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Transit Leadership in the Post-COVID-19 Mobility Landscape

Part One: Measures to Promote Safe Mobility

1. Overview

1.1 Presence and spread of pathogens as a health risk in transit facilities

Transit facilities are among the most common and important elements of public transportation systems across the globe and as such are vulnerable during a pandemic. During the current COVID-19 outbreak, more than 10,000 employees of Metropolitan Transportation Authority (MTA) in New York City have tested positive, and around 130 employees have lost their lives to the virus. In Washington, D.C., on the nation's second-busiest transit system, around 6,000 employees of the Washington Metropolitan Area Transit Authority (Metro) have tested positive [2]. With the emergence of COVID-19, providing safe and healthy transit mobility, as well as a high level of confidence among riders and employees, is of paramount concern and requires that appropriate safety measures, procedures and protocols be implemented to minimize the spread of the pathogen.

COVID-19 poses a transmission risk among transit riders. This risk varies with co-travel time and seat location [3, 4] when no specific countermeasures are considered. When riders are confined to spaces such as stations, waiting areas, platforms, trains and buses, measures should be taken to reduce the risk of transmission, including those impacting the architecture and ventilation of the facility. For airborne pathogens such as COVID-19, architectural and ventilation measures are expected to be at the forefront of effectiveness, along with conventional and behavioral measures (discussed in Part Two of this paper) [5, 6].

While good personal hygiene, physical distancing, use of personal protective equipment (PPE), and implementation of other conventional measures are important to control the pathogen spread, they are all dependent on the individual rider and his or her own compliance in terms of their use. However, there is an opportunity to influence the physical components of transit stations and vehicles (buses/railcars) and to strive to provide a controlled and managed environment through the use of architectural and ventilation interventions that could improve the transit station or car design and make them less conducive to promoting the spread of the pathogen. Mitigation of COVID-19, or other infectious agent hazards, is a critical objective for transit systems and operating agencies in order to maintain public safety and viable patronage levels for adequate financial operations.

As designers, architects and engineers have a profound responsibility to ensure the health and safety of transit facilities, this white paper attempts to advance this aim in providing agencies with measures that can increase the safety of their riders and promote safer travel to their destinations. In addition, measures must be taken to provide for the safety of transit employees—conductors, bus drivers, custodians, maintenance and operation staff, and others—such that all are confident in the safety of their work environment and actively participate in supporting and sustaining it.

1.2 White paper objectives

Part One of this white paper has been created as a collaborative effort of the Technical Solutions sub-group of APTA's Vision for Transit Post COVID-19 Research and Thought Leadership Workgroup, of APTA's Mobility Recovery & Restoration Task Force, in collaboration with HNTB architectural and ventilation experts for the purpose of establishing a range of potential architectural and ventilation solutions and to provide guidance to transit agencies to enhance their transit facilities. The solutions proposed in this document would help promote safety in transit facilities and restore riders' confidence in public transit as a safe method of travel.

The individual measures identified in this white paper, both architectural and ventilation-related, are intended to provide transit agencies with a menu of potential solutions. These have been compiled from various measures already in use nationally and internationally. In addition, new measures with a high potential of being effective have been identified and presented as potentially new solutions; their effectiveness is well-known and proven in other industries or markets. The use of any one measure or intervention, alone or in combination with others, is dependent on a given facility's ability to accommodate these options from a functional, technical and financial point of view.

No measures presented herein are meant to preclude other options, and the use of any or all options is at the discretion of the managing entity. This paper attempts to start a dialog with transit agencies about their readiness and ability to venture into the implementation of any number of measures that have demonstrated a capability of improving transit safety in a post-pandemic world. This white paper might also be instrumental in a continuous effort toward identifying a prepared package of future measures that could work toward transit agencies' readiness in preparing themselves for impending pandemics caused by airborne pathogens (bacteria or viruses).

In addition, this white paper aims to do the following:

- Assess rider expectations for post-pandemic transit use while referencing measures that influence and guide safe behaviors (see Part Two of this white paper).
- Develop practical technical and architectural solutions that would be instrumental in permanently restoring transit services in a post-pandemic society.
- Introduce an initial step toward establishing recommendations for architectural and ventilation and air quality design criteria toward promoting safety for transit riders and employees in the postCOVID19 world and in preparation for impending pandemics caused by airborne pathogens.
- Incorporate equity values in technical solutions aimed toward universally accessible measures. Amid a general lack of analytical research and references in relation to COVID-19 spread in transit environments, we trust this paper will be helpful in advancing this subject.
- Inspire additional studies and spur requests for much-needed federal funds to benefit the transit industry and help to proactively manage any future pandemic.

1.3 Study approach

The following steps have been considered to establish this white paper:

- Understand mechanisms of the pathogen spread through the air and via surfaces, especially related to the transit environment and potentially high patronage densities.
- Develop architectural and ventilation measures that would reduce pathogen spread and concentrations via readily implementable design interventions.
- Identify air purification technologies that are safe and practical for implementation in transit facilities and vehicles.

- Establish evaluation criteria to differentiate among various measures and understand their benefits and effects for underground stations, above-ground and at-grade stations, train vehicles, and buses.
- Evaluate various measures and develop recommendations.

2. COVID-19 overview

According to the Centers for Disease Control and Prevention (CDC), coronavirus disease 2019 (COVID-19) was first identified in Wuhan, China, in December 2019. Since then, no country has been immune to the effect of this highly infectious airborne disease. The virus is primarily transmitted from person to person via nose and mouth secretions, including respiratory droplets that are produced when someone with COVID-19 sneezes, coughs or speaks in close contact with a new host. Smaller droplets containing the viral pathogen may remain suspended in the air for up to three hours in enclosed spaces. Droplets can land on objects or surfaces and potentially remain there for hours; people can also become infected by touching a contaminated surface and then touching their eyes, mouth or nose [7].

The virus has changed the world. Many countries have practiced strict travel restrictions while imposing lockdowns to contain and eliminate the spread of the virus. The impact on public transportation systems has been significant. Ridership numbers on trains and buses decreased dramatically; New York City's notoriously packed subway system felt the effects, its ridership numbers alone dropped 92 percent in mid-April [8]. Around the same time, many other major cities experienced similar numbers. Seattle's Sound Transit system-wide ridership was down an estimated 87 percent [9], Washington's Maryland Area Regional Commuter (MARC) ridership numbers were down 96 percent [10], San Francisco's Bay Area Rapid Transit (BART) system was down 92 percent [11], Chicago's numbers were down 79 percent [12], while LA Metro's rail ridership decreased by 75 percent [13].

Health experts believe a vaccine could likely become available as early as 2021; however, safe antiviral vaccines are hard to develop. In the meantime, the CDC recommends the use of a face mask, thorough handwashing and physical distancing when leaving home to prevent COVID-19 spread and transmission.

Even if a successful vaccine for COVID-19 is developed, in addition to other threats such as natural disasters and terrorist actions, there remain more than 1.65 million unknown infectious diseases in animals with no vaccine that may cause the next devastating pandemic [14]. As vaccines are developed at need, responsible professionals including architects and engineers must actively evaluate feasible and practical measures to preempt and respond to the future spread of pathogens, or possible resurgence of COVID-19, in support of the public's health, safety and general welfare.

3. Understanding the mechanisms of pathogen spread

During recent months, scientists have proved that the spread of the COVID-19 virus is driven by inhalable droplets (e.g., from coughing) and airborne particles (aerosols). The droplets are infectious only at short distances, while aerosol particulates can stay in the air for hours while being transported and distributed by air flow [6].

Virus aerosols play a significant role in infection. Expert opinions differ as to just how large this role is. However, researchers agree that the risk of infection is greatest in enclosed spaces.

The former president of the International Society for Aerosols in Medicine, Gerhard Scheuch, pointed out that it is precisely those very small particles (of less than 5 μm) that can float in the air for hours and then be inhaled. Only the nose and lungs contain the ACE2 receptor proteins that enable viruses to enter human cells and multiply, Scheuch explained [15]. "After sneezing, the viruses get back into the air," he said. Scheuch counts himself among a number of researchers who believe that infection via aerosols is the most important means of contagion.

In July 2020, around 240 researchers published a letter in a specialist journal in which they accused the World Health Organization (WHO) of neglecting the risk of infection through aerosols in its recommendations [8]. WHO reacted cautiously at first, but a few days later went into more detail about virus transmission via aerosols with an article.

However, several publications clearly indicate the presence of both droplets and aerosols as major infection sources [16]. Science has long known qualitative droplet and aerosol contributions for different situations (breathing, coughing and sneezing) [17].

3.1 Key parameters

In transit facilities, there are two primary ways in which a pathogen can be spread: through the air (aerosols) and through personal contact (droplets).

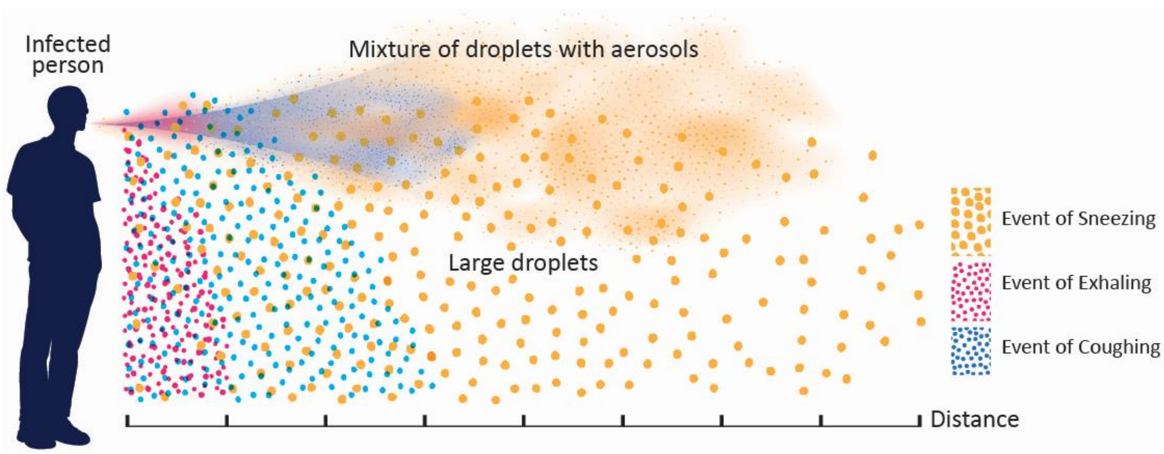
3.1.1 Pathogen spread via contact

The transit environment features numerous instances where riders and employees need to make physical contact with various objects. Ticket vending machines (TVMs), door handles, and escalator and stair rails are examples of objects that could pose threats to the safety of users when subjected to surface pathogens. Potential architectural measures that minimize those threats, with examples, are included in Section 6.1.3.

3.1.2 Airborne pathogen spread

In a crowded transit environment, the airborne spread of pathogens among riders and transit employees represents a tangible threat. The spread of droplets and aerosols is qualitatively shown in **Figure 1** for normal breathing, coughing and sneezing events. It should be noted that aerosols are small particles that float in the air and follow any air movement. Aerosols can be particles and/or small droplets.

FIGURE 1
Person Exhaling, Coughing and Sneezing Without a Mask



In general, aerosols are characterized by the fact that they can float in the air for hours, unlike larger droplets, which sink to the ground after a short time due to gravity. In a dry environment, further aerosols can be produced by partly evaporated droplet liquid. It should also be noted that larger droplets have a higher pathogen load than small aerosols, some of which consist of only one virus nucleus. Technical ventilation and sanitization measures to increase air quality and reduce active pathogens are discussed in Section 7.

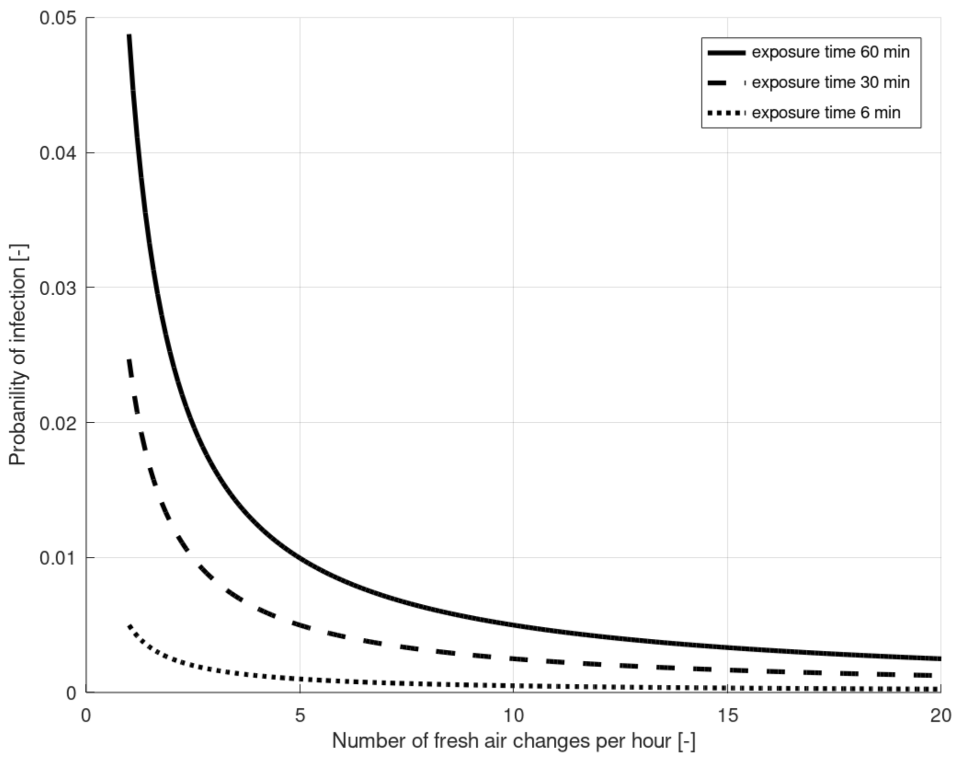
3.1.3 Risk of infection

The probability of contagion by one or more infectious people in an enclosed space can be determined for different air exchange rates using the Wells-Riley equation [5, 18]. This calculation method has been used for many years and offers a mathematically simple description for the spread of airborne diseases. **Figure 2** shows the probability of infection following a 6-minute, 30-minute and 60-minute journey in a passenger car for different fresh air exchange rates. The assumptions for the underlying calculations:

- One person in the car is infected. This person is has a normal breathing rate with a quanta release rate of 10 viral particles per hour [19]. The virus emission rate is based on studies on a different virus, so the achieved results only give a qualitative impression of the situation.
- No masks have been considered.
- The generic car has a volume of 100 m^3 (3531 cu ft).
- The pulmonary ventilation rate is 0.5 m^3/h (0.28 cfm).

Even though this method is generic, and based on experiences with different viruses, it can be assumed that the impact of fresh air exchange rates on the probability of infection is significant.

FIGURE 2
Impact of Fresh Air Exchange Rates on the Probability of Getting Infected

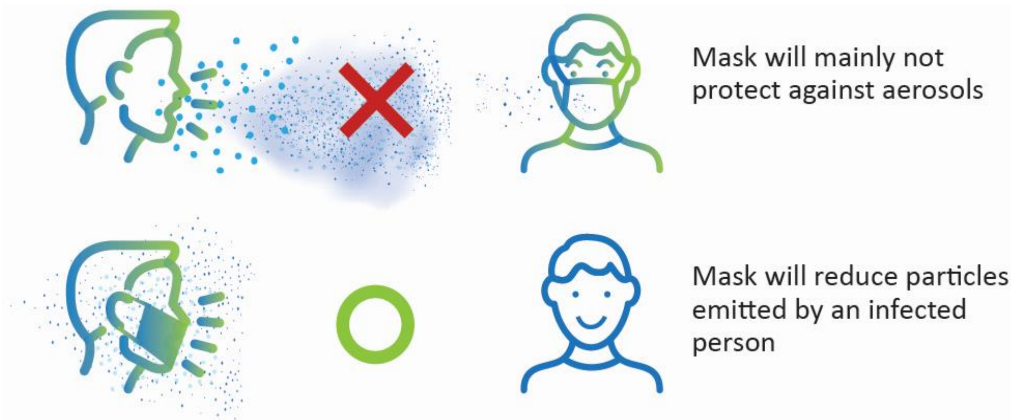


3.1.4 General comment on masks

Masks are extremely useful devices in the mitigation of COVID-19 spread, as they are very effective at reducing the viral load emitted by infected individuals who are actively shedding the virus. Protection of non-infected individuals can also be assisted by the use of masks, but they have a limited capability in this capacity. Aerosols either penetrate most types of mask or, if masks are not airtight to the face, may be inhaled through leakage areas. However, the most positive impact of the mask (reducing spread of droplets) is qualitatively shown in **Figure 3**.

FIGURE 3

Most Mask Types Help Prevent the Spread of Droplets



4. Influencing and guiding safe behaviors

4.1 Public opinion polling results

As lockdown begins to ease nationally, members of the general public are reluctant to share space with strangers where close contact cannot be avoided. Recent CDC guidance also consistently encourages other modes of transportation (walking or automobile driving) as the public returns to normal [20]. In cities that heavily rely on public transportation, significant concern lies in reassuring riders that the transit system is a safe place to enter.

Such findings are supported by a poll collected over two months by Abacus Data on the perception of Canadians regarding the use of transit. The poll asked commuters, "What will it take to ride a city bus?" Only 7 percent of regular transit users said they are currently comfortable using public transit. For the remainder, 69 percent of respondents said they would ride a city bus with conditions (68 percent want surfaces to be cleaned regularly, 63 percent want there to be enough room to distance themselves from others, 62 percent want to see maximum capacity reduced, and 51 percent want to see mandatory face masks). And 24 percent said they won't be comfortable riding a bus until a vaccine is produced [21].

4.2 Measures for influencing and guiding safe behaviors

On their own, safe and practical measures do not ensure successful health and safety management, as their level of success is determined by an individual's behavior. Guidance should be established and promoted among riders and employees to reassure them that the space they are entering is a safe place during a pandemic and afterward.

For example, New Jersey's Transit system launched a customer awareness campaign to promote safe behavior as its customers began to return. The "SAFE NJ" campaign focuses on high-visibility signage throughout the system to maintain awareness of recommended best practices that ensure the healthiest and safest transit system for all [22]. This is supported by Part Two of this white paper, which recommends four possible steps toward building confidence in the use of transit:

1. Provide a safe environment.
2. Provide supporting documentation that shows the environment is safe.
3. Message the details of the space's safety.
4. Ensure the safety of riders' destinations.

5. Conventional disease control measures

NOTE: The best-practice recommendations provided in this section are not prescriptive but are intended to provide information about possible approaches to disease control. Not every suggestion will be applicable to every pandemic outbreak, every community or every transit agency.

5.1 Reducing pathogen concentrations and spread

5.1.1 Physical distancing

Physical distancing is regarded as an important measure to help reduce the spread of airborne pathogens in public areas. However, continuous physical distancing in the transit environment is not sustainable over the long term due to transit's reliance on high passenger density to provide effective and efficient service. For this reason, physical distancing must be treated as an emergency measure to be put in effect only during times of high contagion spread potential.

5.1.1.1 Service level

Agencies should plan to implement physical distancing measures on their fleet of transit vehicles and in their station facilities when required to mitigate the spread of contagious matter between passengers. Strategies should be devised for each vehicle and facility type that provide for adequate separation between patrons. Each strategy should consider several possible levels of distancing to meet possible future requirements or recommendations. In conjunction with this approach, operation and communications protocols must be developed to ensure that the capacity of vehicles and facilities are not exceeded under reduced-capacity conditions.

Vehicle and service capacity relative to passenger demand must also be managed actively. Clear communication regarding the capacity limitations in vehicles and at stations must be provided to manage the flow of passengers in and out of the affected areas and to inform passengers when extended wait times might occur due to limited available capacity in vehicles and at stations. If practical, additional vehicles should be placed in service to meet transit demand.

Active demand management should also be considered through targeted and active communication in areas where high service demand occurs. This communication should clearly state service goals with regard to maximum capacity of the transit equipment and facilities and communicate, when possible, real time information about current ridership levels. This is discussed further in Part Two of this white paper.

5.1.1.2 Vehicle/facility design

The design of future vehicles and facilities should take physical distancing into account or, at the very least, allow easy flexibility to change seating configurations based on the guidelines of future pandemics. The addition of permanent or temporary separation devices, such as physical barriers between seats or standing areas, should also be examined. Passenger flow measures, such as designating doorways for exit or entry only and possibly creating one-way flow lanes inside vehicles (e.g., from front to back of vehicles) should also be considered.

Distancing measures in stations and on station platforms can also be managed through installation of temporary barricades to manage the flow of passenger traffic, and through signs or markings on the floor of the facilities, which would delineate proper distancing increments throughout the facility where queuing is expected.

5.1.1.3 Communication/signage

Communication with the riding public should be in both audio and visual forms. The communication should be frequent but not overbearing. Existing static and electronic signage and public address systems should be used to communicate physical distancing measures and expectations throughout all system facilities and vehicles. Transit operator websites, signage and physical media should also be used to spread the same message outside the transit environment. Operations employees and other support staff who communicate with riders should reinforce the message.

Care must be taken to ensure that messaging to the riding public is succinct and easy to understand. Consistency of messaging across all communication platforms and in direct interaction with agency staff is critical.

5.1.2 Personal protective equipment

5.1.2.1 Communication/signage

Communication with the riding public should be in both audio and visual forms. The communication should be frequent but not overbearing. Transit operator existing static and electronic signage and public address systems should communicate expectations regarding PPE to be worn by both operators and the general public. Transit operator websites and signage should also be used to communicate the same message outside the transit environment. Operations employees and other support staff who communicate with riders should reinforce the message to riders.

5.1.2.2 Requirements for face coverings/gloves

Transit agency PPE programs should comply with 29 CFR 1910.132, internal transit agency policy, manufacturer's recommendations, and other recommendations or guidance that might be issued by health and safety agencies regarding this topic. PPE programs should be easy to change guidelines given the level of infection in a given area, the nature of the infection, and feedback from stakeholders, including the general public, transit operators and health experts.

5.1.2.3 Hand sanitizer or wipe dispensers in vehicles and/or facilities

Transit agencies should provide supplies to support the mitigation of spread of contagious diseases for passengers and employees in both their facilities and vehicles. Examples of supplies provided should be soap, cleaning wipes, hand sanitizer dispensers, paper towels, tissues and trash cans to dispose of used products.

5.1.3 Established procedures for cleaning and disinfection

5.1.3.1 Written work instructions/checklists

In the past, cleaning and disinfection were assumed to be done correctly. The recent pandemic has exhibited that as many details as possible regarding the procedures for cleaning and disinfecting a transit vehicle or facility need to be documented, so expectations are set and there is little variability in performance based on the cleaner.

5.1.3.2 List of approved cleaners

Given the ever-changing environment related to this pandemic and future public health crises, a list of approved cleaners should be maintained by each agency/operator for the purposes of safety and quality control of the cleaning process. The list should be reviewed by applicable staff at regularly scheduled intervals. Changes should be updated into any applicable work instructions.

5.1.3.3 List of approved tools for cleaning and disinfection

Given the ever-changing environment related to this pandemic and future public health crises, a list of approved cleaning and disinfection tools should be maintained by each agency/operator for the purposes of safety and quality control of the cleaning process. The list should be reviewed by applicable staff at regularly scheduled intervals. Changes should be updated into any applicable work instructions.

5.1.4 Routine decontamination of equipment and facilities

5.1.4.1 Interval of cleaning

Transit agencies should set a goal that all active, in-service/-use transit facilities and vehicles should be cleaned and disinfected daily, at a minimum. The entire facility or vehicle should be cleaned, but particular attention should be paid to high-touch and/or high-traffic areas.

5.1.4.2 Methods used for disinfection

In the past, “cleaning” was used as a blanket term. However, cleaning and disinfecting are different processes. Cleaning should always be completed prior to disinfecting. Using the two processes together will produce a facility or vehicle that offers maximum protection against the spread of contagious diseases to transit employees and passengers. Cleaning is a process that physically removes dirt and contaminants from a surface. Disinfecting has to be completed with a particular chemical or process that is labeled a disinfectant chemical or process.

5.1.5 Staff training

5.1.5.1 Training for cleaners on proper cleaning and disinfection

Training for cleaners on proper cleaning and disinfection should be handled in a similar manner to training for a craftsperson on maintaining a vehicle or a facility. The training should teach proper cleaning methods, familiarity with proper cleaning tools and the use of proper cleaning compounds. Cleaners should be familiar with work instructions that have been issued and proper safety protocols, including use of proper PPE.

5.1.5.2 On-the-job training

Following formal training, cleaners should be exposed to work practices through on-the-job training as well. Cleaners to perform the on-the-job training should be chosen based on experience and past job performance. Emphasis should be placed on safety protocols and efficient practices in cleaning either facilities or vehicles.

5.1.5.3 Training for management of proper level of cleaning

Management and supervisors should also be trained on cleaning practices and work instructions. In order to properly gauge cleaning and disinfecting and set clear expectations across all employees in charge of cleaning, it is essential that managers and supervisors be trained in the same set of instructions so clear expectations can be enforced in order to create limited variability among different cleaners.

5.1.6 Last-cleaned signage

5.1.6.1 Cleaning logs visible for vehicles, facilities and bathrooms

Post-cleaning logs should be displayed for the general public and other employees to view. The cleaning logs should contain, at a minimum, an explanation of what cleaning/disinfecting processes are being signed for, the date the facility/vehicle was cleaned and the initials of the employee performing the action. This action will promote a level of transparency that will aid in building trust for users of the transportation system. It also adds a level of accountability to the employees performing the cleaning/disinfecting.

5.2 Conventional measures for reducing airborne pathogen spread

5.2.1 Adjustment of existing ventilation parameters for increased circulation

Most viruses and other pathogens can be transmitted through airborne particles or droplets. Adequate ventilation and air filtration of HVAC systems are important components in mitigating the risk of exposure to transit users. Increased ventilation through the HVAC systems increases the volume of air pushed through the HVAC filtration system, thereby increasing the number of particles that are removed from the air.

Increased air exchange, or the replacement of air in a confined interior space with fresh outdoor air, has been shown to be the most effective way to decrease the spread of infection in an interior environment. However, many transit facilities, such as underground rail stations and vehicles, have limited capability to exchange interior air due to the design of the ventilation system and, in some cases, the restrictive nature of the operating environment (e.g., underground tunnels).

The design of HVAC systems for future vehicles and facilities will need to be evaluated with new air exchange goals in mind. In general, an increase in regular exchange comes at a cost related to the conditioning of the air to provide adequate passenger comfort, as fresh intake air requires a greater level of conditioning than air that is recirculated within the interior environment. The level of fresh air intake can be managed through the HVAC control systems, but these systems must be designed to include provisions for adequate fresh air intake. Primarily due to energy consumption considerations, HVAC system design has focused on decreasing fresh air intake and the treatment of recirculated air as a means of achieving interior air comfort. The need to treat the air for airborne contaminants is now reversing this approach.

5.2.2 Regular cleaning of existing air filtration systems

5.2.2.1 Type of filtration

Air filtration occurs when air passes through a permeable membrane or other material that removes particles from the air as it passes through. The level of filtration can be adjusted according to the filtration requirements, generally through the use of properly rated air filters in most HVAC systems.

There are many types of air filtration now designed into HVAC systems, with more new technologies on the horizon due to increased visibility as a result of the COVID-19 pandemic. Most systems currently running use traditional air filters, rated MERV 7–10, to physically filter the air, which is an adequate level of filtration to remove large particles from the airflow. In order to be effective against airborne droplets and other pathogen-carrying particles, however, the level of air filtration must be increased to at least MERV 13. This can be achieved in most systems through the exchange of air filters to the more restrictive variety, but this does come at a cost to air circulation. Higher MERV-rated filtration systems tend to reduce the amount of air that passes through them, decreasing the level of air circulation within the conditioned space. Apart from reducing the frequency of air exchange within the affected space, decreased air circulation can, in some cases, also cause other issues with the general performance of the HVAC system.

Other approaches to air treatment are currently being deployed or investigated. Systems using ultraviolet (UV) light to sanitize the HVAC system are being deployed by some operators, while others have installed electrostatic filtration systems, which aim to remove particles from the air by electrically charging them and then removing them using screens that carry an opposite electrical charge. The impact of these measures on air cleanliness is mixed and greatly dependent on local conditions, HVAC system design and other infrastructure parameters. Therefore, there is no single system or approach that can currently be recommended under all circumstances.

5.2.2.2 Maintenance logs

Maintenance logs should be used for any type of air filtration system to keep track of regularly scheduled maintenance. All the systems described above have either replacement or cleaning intervals so their systems continue to perform as designed and at peak efficiency. Maintenance logs should be posted at a location regularly viewed by maintenance personnel. Logs should be kept in a facility or vehicle but can also be backed up in a computer maintenance database.

6. Architectural interventions

> **NOTE:** The best-practice recommendations provided in this section are not prescriptive but are intended to provide information about possible approaches to disease control. Not every suggestion will be applicable to every pandemic outbreak, every community or every transit agency.

6.1 Architectural design measures considering innovative technologies

As discussed in Section 5.1, conventional measures such as promoting physical distancing requirements, wearing PPE, establishing procedures for cleaning and disinfection, routine decontamination of equipment and facilities, etc. have been identified and already implemented by many transit agencies.

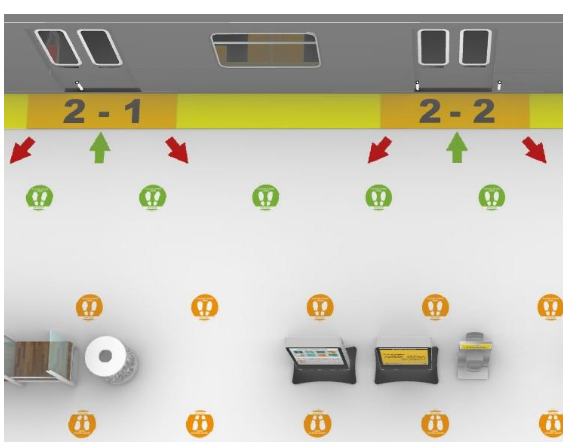
However, in order to fight against the spread of COVID-19, as well as to preempt and respond to future pathogen spread, for both planned and existing facilities, a systematic approach of combining architectural design measures and interventions with innovative technologies should be considered. Many of these interventions and technologies are discussed in the following sections.

6.1.1 Physical distancing

6.1.1.1 Signage for distancing requirements and boarding management

Using physical distancing signs is a simple and easy way to remind riders to keep a safe distance of 6 ft away from one another. Many transit agencies have already implemented these floor decals in their transit facilities in a quick and temporary manner, given the emergency situation. Moving forward, care and thought must be given to establishing consistent standards regarding boarding, waiting, and distancing requirements and the accompanying graphics for ease of rider movement. **Figure 4** shows physical distancing signage implemented directly on a platform, providing guidance about the safe distancing requirements and helping to manage embarking and disembarking while streamlining the process. By using differentiated colors or graphics, the embarking process can be prioritized.

FIGURE 4
Illustration of Physical Distancing Signage on a Platform



Effectiveness: When physical distancing graphics are placed in a transit facility or vehicle, they should feature bold graphics and also a tactile finish, similar to a platform edge, which would enable all riders using the system to access these visual/tactile cues. Repeated, consistent messaging would result in a tendency to adhere to the signs, thereby providing a universally accessible measure.

Ease of application: This is one of the simplest ways to educate and inform riders about physical distancing. Using paint or adhesive graphics that are durable enough to withstand foot traffic can create signage that keeps riders distanced. Many agencies have already or are in the process of implementing such measures.

Capital cost: As these measures can be an additive solution to any existing surface, it is expected that they could be implemented with low initial investment.

O&M cost impact: As incorporation of this measure would reduce the need for on-site staff, it has the potential to reduce O&M costs.

Equity: With bold graphics and a tactile finish, these measures would benefit all riders using the public transportation system.

6.1.1.2 Display of density (phone apps and electronic signage)

Maintaining a safe distance seems feasible in many situations, but as shown in **Figure 5**, during peak hours before the pandemic, riders rarely had any space between them on many transit lines, especially those in dense urban areas.

FIGURE 5
Peak-Hour Condition Before the Pandemic

Penn Station, New York

In order to keep transit services running while protecting the safety of riders, providing real-time data of how many riders are on oncoming transit railcars or buses would help riders make decisions on which vehicle to board, minimizing crowding and facilitating physical distancing. Integrating real-time information can enable seamless and just-in-time connections, eliminating unnecessary wait times. This data can be collected via sensors mounted above vehicle doorways that would provide accurate passenger counts using a combination of infrared and 3D image pattern technologies.

Providing this real-time data through mobile phone applications and dynamic signage would inform riders of the onboard densities of incoming vehicles and help them choose the car, train or bus they would board.

Similar smartphone applications, as shown in **Figure 6**, have already been launched and are being tested by the Taipei Rapid Transit Corporation in Taiwan [23].

A mobile phone application assigns density information for each car according to a color code; for example, the color green symbolizes a "comfortable" number of riders in a vehicle, yellow an "average" density, orange "rather crowded," and red "very crowded." These apps allow riders real-time viewing of which cars of an incoming train have less density.

Figure 7 shows an electronic screen with real-time passenger density information implemented by the Taipei Rapid Transit Corporation [23].

FIGURE 6
Smartphone Density App

FIGURE 7
Density on an Electronic Sign

Effectiveness: Once the smartphone app is available, it can be an effective measure for riders, who can download and use it at their convenience. Such an app can allow the visually impaired to access density information through audio. However, consideration should be given for riders who do not feel comfortable using smartphone apps or who cannot afford smartphones. To mitigate these equity issues, real-time passenger density information can be displayed on electronic screens so the information can be available to these riders, as shown in **Figure 7**.

Ease of application: To track real-time passenger density information, passenger counting (weighting) sensors should be installed in each vehicle. Information gathered from the sensors can be shared over the integrated mobile apps. Associated mobile apps should be developed for the use of riders.

Capital cost: Since the technology associated with this measure is an addition to the existing arrangement, it is expected that it would be implemented with a moderate initial investment.

O&M cost impact: As incorporation of this technology would reduce the need for on-site staff guiding and managing the boarding process, it has the potential to reduce O&M costs. However, maintaining such technology and providing continuous service to riders should be considered.

Equity: If this measure were implemented universally and available to all riders, differences in outcomes may be expected due to the range of each patron's ability to access this technology.

6.1.1.3 Reconfigured seating

A recent study was conducted to explore potential connections between infection by airborne pathogens, riders' physical distancing and co-travel time. This study has found that the risks of riders being infected while traveling together in the same vehicle is much higher among the individuals seated in the same row than among those seated in different rows [3]. Therefore, retrofitting existing seating through the implementation of protective barriers made of transparent materials, introduction of reversible seating that can change direction, or seating with taller backs that can serve as barriers, can all be effective measures to assist physical distancing and minimize the spread of pathogens. **Figure 8** shows reconfigured seating that facilitates flexible seating arrangements and promotes physical distancing.

FIGURE 8
Reconfigured Seating by United Safety & Survivability Corp.

Effectiveness: Minimizing patron density and proximity while waiting or co-traveling can be a very effective measure in providing healthy transit options.

Ease of application: Such measures can be implemented by simply adding protective barriers or rearranging the seating layout.

Capital cost: This measure involves rearranging or retrofitting existing seating or the purchase of new seating. Therefore, it is expected that it would be implemented with moderate initial investment.

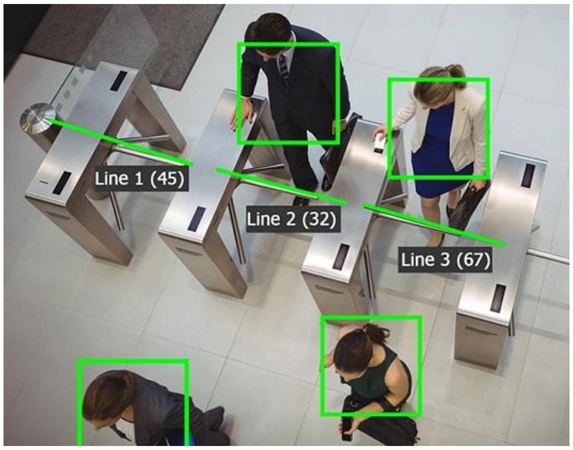
O&M cost impact: Permanently reconfigured seating reduces the staff requirements for temporary rearrangement of seating. As with any seating layout, O&M cost for robust cleaning would be required.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.1.4 Passenger counting

By installing electronic rider counting devices at entry points, the number of people who pass through a fare gate or entrance can be measured. This information would be valuable for advising riders of the rider density at a station and providing them with advanced knowledge of potential station or train overcrowding, in turn influencing their travel schedule. **Figure 9** shows a people-counting system at the turnstile.

FIGURE 9
People-Counting System



https://camlytics.com/anti-tailgating-camera

Effectiveness: This measure would provide density information in stations and be able to monitor occupancy and traffic in real-time. This information would also be useful to strategically develop future transit services. Another potential benefit of this measure is to allow for the reservation of a travel time slot, similar to an entry time at a museum or theme park. This could be done in 30- to 60-minute increments to limit the number of occupants in the system. This would allow for better travel planning rather than waiting to arrive at the station only to see that the system is at capacity.

Ease of application: This measure can be a simple additive solution to existing entry fare arrays and exits. Compatibility with the existing fare gate system should be considered.

Capital cost: Since the technology associated with this measure is an additive to the existing fare gate, it is expected that it would be implemented with a moderate initial investment.

O&M cost impact: Maintaining and operating the newly implemented system should be considered.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.1.5 Barriers

Passive static physical barriers can be a very effective and aesthetically pleasing way to maintain and enforce physical distancing requirements. These barriers, such as railings, planter boxes or even floor-mounted signage, could also be instrumental in guiding and managing rider flow through a transit station.

Effectiveness: Such measures passively force passengers to maintain social distancing requirements.

Ease of application: This measure could be implemented by simply installing physical barriers to guide patrons' movement and promote one-way pedestrian traffic that minimizes direct encounters.

Capital cost: Since this measure could be an additive solution to any existing condition it is expected that it could be implemented with low initial investment.

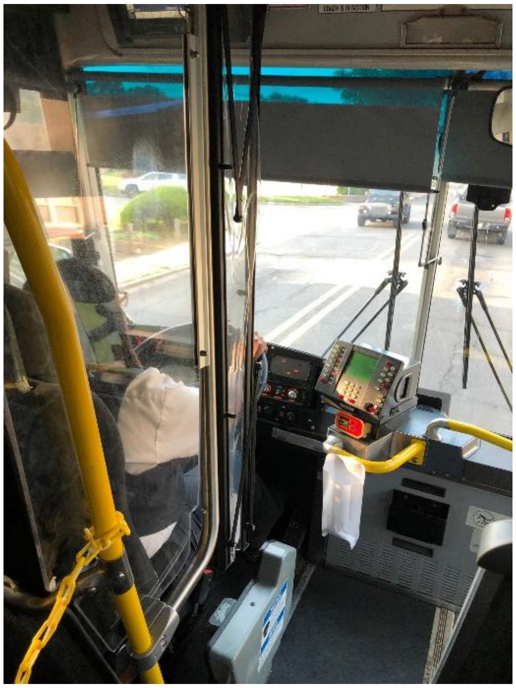
O&M cost impact: Standardized physical barriers eliminate the need for on-site staff to set up and rearrange temporary barriers. As incorporation of this measure would reduce the need for on-site staff, it has the potential to reduce O&M costs.

Equity: If this measure were implemented universally in a transit facility, all riders would benefit equally.

6.1.1.6 Driver/conductor protection shields

Transit employees should be providing their services in a controlled and safe environment. To enhance worker safety, protective shields in the form of transparent Plexiglass barriers or some other transparent material can be used to safeguard bus drivers. **Figure 10** shows the protection shields implemented on a New Jersey Transit bus.

FIGURE 10
Bus Driver Protection Shield at New Jersey Transit



Effectiveness: Establishing physical barriers between drivers and patrons would minimize the spread of pathogens from person to person, promoting a safer distancing for both.

Ease of application: Protection shields can be easily installed in existing conditions. Many agencies have already or are in the process of implementing such items.

Capital cost: Since this measure can be an additive solution to any existing condition, it is expected it could be implemented with low initial investment.

O&M cost impact: As incorporation of this measure would reduce the need for operators to put their own systems in place, it has the potential to reduce O&M costs. Maintaining the condition of the shields and regular disinfection should be considered.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.2 Architectural treatment of ventilation interventions

6.1.2.1 Air purification system

Proper ventilation is one of the key components to providing healthy transit facilities. The ventilation interventions outlined in Section 7 would be located strategically within the station such that their protective capabilities would be accessible to the maximum number of riders. Such appurtenances, in the form of portals at fare gates, stairs, escalators, ventilation ducts, and associated electrical and mechanical equipment, require proper architectural treatment that would enhance the station's aesthetics, maximize their efficiency and provide clear messaging of active air treatment measures being implemented, as shown in **Figure 11**.

FIGURE 11
Illustration Showing Proposed Air Purification System at Entry Fare Gate

Effectiveness: Developing architectural standards in combination with HVAC/ventilation standards would be practical and very effective for use in both existing and new transit stations, providing aesthetically pleasing and mechanically effective solutions. Signage would clearly advertise and promote the system, leading to a high level of confidence for travelers.

Ease of application: A "kit-of-parts" standardized approach would allow for a quick and flexible installation that provides for an immediate visual delineation of these interventions. The flexibility would be suitable for use in any application—from a large fare array application to a single use—over a door, at the top or bottom of an escalator, etc.

Capital cost: Since the ventilation technology associated with this measure is an addition to the existing condition, it is expected that it would be implemented with a high initial investment.

O&M cost impact: As incorporation of this measure would reduce the need for on-site cleaning staff, it has the potential to reduce O&M costs.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.2.2 Platform screen doors

Full-height platform screen doors (PSDs) can help to separate station air on the platform from the air coming from adjacent tunnels. Furthermore, PSDs help to reduce the amount of fresh air on the platform to be pulled into the tunnels by leaving or passing trains. PSDs can therefore help to maintain the quality of the air on the platform level, avoid or reduce rail dust and dirt entering the station, and reduce the energy needed to prepare and provide the required air quality. An example is shown in **Figure 12**.

Further advantages of PSDs are higher personal safety (no collisions between rolling stock and humans) and the separation of the tunnel climate and station climate. Additionally, PSDs are required to prepare stations and rail systems for automatic train driving.

FIGURE 12
Example for Platform Screen Doors

Used with permission of Gilgen Door Systems

Effectiveness: The use of full height PSDs leads to improved air quality on the platform level and in the entire station. Any application of ventilation or sanitization measures becomes more efficient.

Ease of application: Full-height PSDs require specific ventilation schemes for tunnels and stations, and integration/connection of PSD control systems with the train control system is required (e.g., door open, no train movement). Full-height PSDs are considered complex for existing stations. This is different for new stations, when the PSD integration can be coordinated with all related domains (architecture, ventilation, train control, fire and life safety, etc.).

Capital cost: Since the PSD and the ventilation technology associated with this measure would be an addition to the existing condition, it is expected that they would be implemented with a high initial investment.

O&M cost impact: The incorporation of this measure would increase the need for maintenance and therefore increase O&M costs.

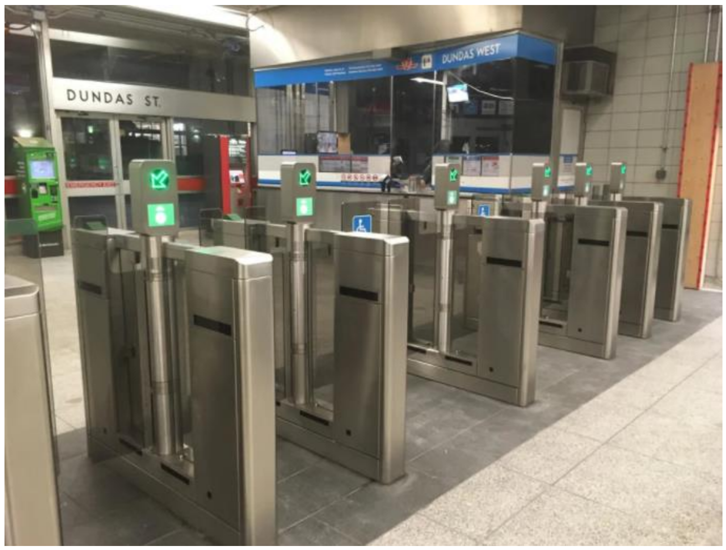
Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.3 Touch-free devices

6.1.3.1 Automatic fare collection (touch-free system at fare gates)

Instead of bar turnstile-type fare gates, wing gate–type fare gates can be installed to promote touch-free fare collection. Gates are in the closed position and automatically open when the fare is collected, allowing riders to pass through without contact. The gates close automatically after passage. Supplemented with the proper use of effective signage, this automatic fare gate can be promote one-way flows, avoiding bidirectional conflicts. **Figure 13** shows wing gate–type fare gates installed in Dundas West Station in Toronto, Ontario.

FIGURE 13
Wing Gate–Type Fare Gate



https://www.reddit.com/r/toronto/comments/7bf)3gy/new_presto_gates_at_dundas_west_station/

Effectiveness: Such a technology would eliminate the need for contact, thereby reducing the risk of contracting a virus through the spread of droplets.

Ease of application: A standardized approach would allow for a relatively quick installation that provides for a touch-free turnstile experience. Many agencies have already implemented or are in the process of implementing such technology.

Capital cost: Since the technology associated with this measure is a replacement of the existing condition, it is expected that it would be implemented with a moderate initial investment. However, the relative cost of implementation could vary greatly depending on the agency and on the status of that agency's current fare-control system and planned modifications, if any.

O&M cost impact: As incorporation of this measure would reduce the need for on-site cleaning staff, it has the potential to reduce O&M costs. However, maintaining the system should still be considered.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.3.2 Phone app–based fare collection

To alleviate rider concerns that pathogens can live on surfaces for an extended time frame and to avoid increasing maintenance costs for an older payment structure, many transit agencies, including NYC's Metropolitan Transportation Authority (MTA), are transitioning to contactless payment systems. Relying on their mobile devices, riders can pay fares in a "tap-and-go" method without using fare cards. This avoids physical contact.

In the New York City region, MTA will fully switch to its touchless OMNY system by 2023. The system, which launched in 2019, allows riders to use their smartphones to tap and pay for any MTA-controlled transit mode. **Figure 14** shows a contactless payment system installed at the 36th Avenue Station in Astoria.

FIGURE 14
OMNY Contactless Payment System

Effectiveness: This technology eliminates the need for physical contact to pay, reducing the risk of viral spread via surfaces.

Ease of application: A standardized approach would allow for a relatively quick installation. Many agencies have already implemented or are in the process of implementing such technology.

Capital cost: Since the technology associated with this measure is a replacement of the existing fare-collection system, it is expected that it would be implemented with a moderate initial investment. However, the relative cost of implementation could vary greatly depending on the agency and on the status of that agency's current fare-control system and planned modifications, if any.

O&M cost impact: As incorporation of this measure would reduce the need for on-site cleaning staff, it has the potential to reduce O&M costs.

Equity: If this measure were implemented universally, differences in outcomes may be expected due to the range of each patron's ability to access the technology.

6.1.3.3 Voice-activated systems

Integrating voice-control systems in elevators, ticket vending machines and other devices would be another way to promote touch-free facilities. This method might have limitations in terms of helping riders with language barrier or those who might be hearing impaired, yet it might be an effective supplemental measure that helps many riders.

Effectiveness: This technology would eliminate the need for physical contact, reducing the risk of virus transmission by the spread of droplets. However, consideration should be taken to implement a system that is designed to handle noisy environments, a variety of English accents and a variety of languages.

Ease of application: This measure can be implemented by adding smart voice control systems to existing devices.

Capital cost: Although this measure is an additive solution to existing system, consideration should be given regarding compatibility with the existing system. Therefore, it is expected that it would be implemented with a high initial investment.

O&M cost impact: Incorporation of this measure would significantly reduce the need for on-site cleaning staff, so it has the potential to reduce O&M costs. However, maintenance of the newly implemented system should be considered.

Equity: If this measure were implemented in a transit facility and available to all patrons, differences in outcomes may be expected due to the technology's inability to understand a full range of voices.

6.1.3.4 Automatic door-opening systems

Automatic door opening systems are widely used in commercial buildings. Using various kinds of sensors, these systems open the door when a person comes near and close it after the person moves away.

Effectiveness: Such a measure would eliminate the need for physical contact, greatly reducing the risk of viral transmission via droplets.

Ease of application: This measure could be implemented by replacing existing manual doors with automatic door opening systems, which would also require an associated electrical power supply.

Capital cost: Since such measures require replacing existing manual doors and retrofitting associated electrical power sources, it is expected that they could be implemented with moderate initial investment.

O&M cost impact: Incorporation of these measures would significantly reduce the need for on-site cleaning staff and therefore have the potential to reduce O&M costs. However, maintenance of the newly implemented systems should be considered.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.3.5 Touch-free devices and accessories

Installing touch-free devices and accessories will be one of the main measures used to prevent the spread of pathogens via droplets. These devices include voice-activated vending machines for ticketing and PPE purchase and, in public restrooms, touches flush valves, faucets, hand soap, paper towel dispensers, hand dryers, trash receptacles, etc.

Effectiveness: Such measures eliminate the need for physical contact, greatly reducing the risk of viral transmission via droplets.

Ease of application: These measures could be implemented by replacing existing devices and accessories with the touchless devices. Many agencies have already implemented or are in the process of implementing such measures.

Capital cost: Although these measures are a solution that requires replacement of existing devices, it is expected that they could be implemented with low initial investment.

O&M cost impact: Incorporation of these measures would significantly reduce the need for on-site cleaning staff, and therefore have the potential to reduce O&M costs.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.3.6 Onboard toilet facilities with touch-free devices

Touch-free devices can be installed in onboard toilet facilities to prevent the spread of pathogens. These devices include flush valves, faucets, hand soap, paper towel dispensers, hand dryers, trash receptacles, etc.

Effectiveness: Such measures eliminate the need for physical contact, greatly reducing the risk of viral transmission via droplets.

Ease of application: These measures could be implemented by replacing existing devices and accessories with the touchless devices. Many agencies have already implemented or are in the process of implementing such measures.

Capital cost: Although these measures are a solution that requires replacement of existing devices, it is expected that they could be implemented with low initial investment.

O&M cost impact: Incorporation of these measures would significantly reduce the need for on-site cleaning staff, and therefore have the potential to reduce O&M costs.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.3.7 Touch-free onboard stop indicators

To minimize the spread of pathogens through direct and indirect contact, touch-free onboard stop indicators can be implemented on buses, allowing riders to indicate stop signals using an onboard Wi-Fi-based system and an app downloaded on their smartphones.

Effectiveness: Such measures eliminate the need for physical contact, greatly reducing the risk of viral transmission via droplets. For those who cannot afford smartphones or do not feel comfortable using apps, an electronic touchscreen with self-cleaning film applied would be an option to mitigate the equity issue.

Ease of application: Patrons download the smartphone app and use it to indicate a stop signal onboard. However, consideration should be taken for riders who do not feel comfortable using smartphone apps.

Capital cost: Since this measure is a solution that requires development of new smartphone apps, it is expected that it could be implemented with moderate initial investment.

O&M cost impact: This measure would significantly reduce the need for on-site cleaning staff, so it has the potential to reduce O&M costs. However, maintenance of the software should be considered.

Equity: If this measure were implemented in a transit facility and available to all patrons, differences in outcomes may be expected due to the range patrons' ability to access this technology.

6.1.3.8 Touch-free onboard ticketing

To minimize the spread of pathogens through direct and indirect contact, bus or train tickets could be purchased onboard using mobile apps, providing that the train route has an onboard Wi-Fi system. After downloading an e-payment app on their smartphones, riders can set up their account and link it to a credit or debit card and pay fares, minimizing unnecessary contact and avoiding waiting in line.

Effectiveness: Such a measure would eliminate the need for unnecessary contact, thereby reducing the risk of transmission through the spread of droplets.

Ease of application: While incorporation of touch-free onboard ticketing app may pose challenges, many transit agencies have implemented or are implementing this measure.

Capital cost: Since this measure would require development of new smartphone apps, it is expected that it could be implemented with moderate initial investment. However, the relative cost of implementation could vary greatly depending on the agency and on the status of that agency's current fare-control system and planned modifications, if any.

O&M cost impact: Incorporation of this measure could reduce the need for on-site staff. However, maintenance of the software and the ability to provide good online service while operating should be considered.

Equity: If this measure were implemented in a transit facility and available to all patrons, differences in outcomes may be expected due to the range patrons' ability to access this technology.

6.1.4 Surface treatments

6.1.4.1 Antimicrobial film or powder coatings

Conventional disinfectant products kill pathogens effectively during application, but surfaces are easily recontaminated when touched by an infected person. In addition, disinfectants are effective only when the proper methods are followed. **Figure 15** shows the science of antimicrobials.

The use of antimicrobial film, powder coatings, or durable hospital grade antimicrobial applications, as are used in the healthcare industry, can effectively help to keep surfaces clean. For instance, a liquid antimicrobial is commonly used. It forms a protective coating that molecularly bonds with surfaces. Microorganisms are attracted to the coating's positive charge and die upon coming into contact with the surface. This type of shield is effective for an extended period of time—as much as one year—and inhibits the growth of microbes on surfaces by neutralizing their natural cell wall protection. These applications could be implemented to treat high-touch surfaces in transit facilities, such as grab bars and handles, seating areas, counters, interior panels, escalator handrails, and so on.

Antimicrobial treatments can complement the effectiveness of existing cleaning and disinfection procedures. **Figure 16** shows antimicrobial-coated handrails on Hong Kong's Mass Transit Railway (MTR).

FIGURE 15
The Science of Antimicrobials

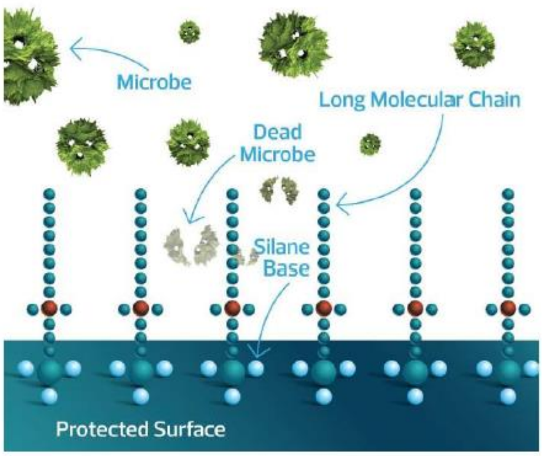


FIGURE 16
Antimicrobial-Coated Handrails in a Transit Vehicle

https://amp.insider.com/hong-kong-mtr-better-than-the-london-underground-new-york-subway-2018-1

Effectiveness: Antimicrobial coatings have been known to stop the spread of pathogens and have the potential to meaningfully lower the environmental impact of cleaning [24].

Ease of application: Such measures can be applied in the form of powder coatings or adhesive films.

Capital cost: This measure is an additive solution to any existing surfaces. Applying antimicrobial coatings to existing surfaces will require labor and therefore a moderate initial investment.

O&M cost impact: Incorporation of this measure would significantly reduce the need for on-site cleaning staff, so it has the potential to reduce O&M costs.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.4.2 Copper coatings

For centuries, copper alloys have attracted attention due to their natural biological and pharmacological properties. Their diverse antimicrobial properties are proved to have a potent biocidal effect on a wide range of pathogens [25]. In 2008, the United States Environmental Protection Agency (EPA) recognized copper as an antimicrobial metal capable of killing harmful and potentially deadly bacteria [26]. Copper is the first solid surface material to receive this type of EPA registration.

Effectiveness: Recent studies show that COVID-19 was detectable for only up to four hours on copper, while up to 24 hours on cardboard and as much as two to three days on plastic and stainless steel [27]. Similar to antimicrobial coatings, copper has been widely used to treat high-touch surfaces in healthcare industries. In order to avoid the spread of pathogens from indirect contact in a transit environment, copper can be used in a number of applications, such as grab bars and handles, seating textiles, interior panels, etc.

Ease of application: Such measures can be applied through a form of ultrathin coatings or patches, thereby reducing the amount of metal used and the cost.

Capital cost: Although this measure is an additive solution to any existing surface, the cost of the material itself is a consideration, resulting in a high initial investment if used extensively.

O&M cost impact: Incorporation of this measure would significantly reduce the need for on-site cleaning staff, so it has the potential to reduce O&M costs.

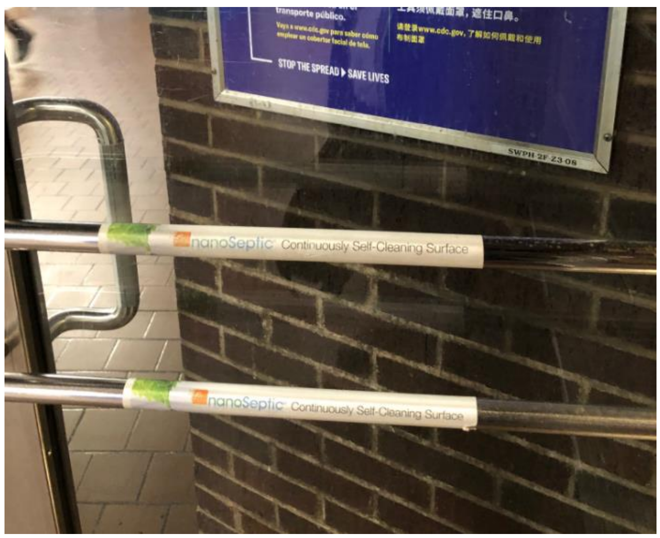
Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.4.3 Self-cleaning nanocoatings

Nano-materials are used in numerous products and industrial applications, and self-cleaning nanocoatings have been considered as next-generation cleaning technology due to their ability to kill both bacteria and viruses surfaces, as well as in the air near coated surfaces. Similar to the coatings mentioned in previous sections, self-cleaning nanocoatings could be used as another option in transit applications to treat high-touch surfaces.

Figure 17 shows a self-cleaning nanocoating installed on handrail surfaces at the Port Authority Bus Terminal in New York City.

FIGURE 17
Self-Cleaning Nanocoatings



Effectiveness: Self-cleaning nano-surfaces work using mineral nanocrystals that harness the power of visible light to create a powerful oxidation reaction, which continuously breaks down organic contaminants [28].

Ease of application: Such measures could be implemented simply by adhering the film to high-touch surfaces. Many agencies have already implemented or are in the process of implementing such measures.

Capital cost: Since this measure could be an additive solution to any existing surfaces, it could be implemented with low initial investment.

O&M cost impact: This is a relatively new product and requires occasional replacement. However, as incorporation of this measure will significantly reduce the need for on-site cleaning, it has the potential to reduce O&M costs.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.1.4.4 Self-cleaning devices using UVC lights

There are three types of UV light. The first is UVA, which is capable of penetrating deep into the skin and is thought to be responsible for up to 80 percent of skin aging. The second type is UVB, which can damage our skin, leading to sunburn and skin cancer. The third is UVC, which is known for its disinfection ability and is already used in medical disinfection devices [29]. As it is also harmful to humans and the environment, care must be taken when utilizing UVC light so as not to allow direct exposure to surrounding areas.

The Port Authority New York New Jersey has been testing self-cleaning escalator handrail sterilizers in Terminal B at Newark Airport and at the Port Authority Bus Terminal in Midtown Manhattan, as shown in **Figure 18**. **Figure 19** shows an escalator with UVC light handrail disinfection from Schindler.

FIGURE 18
Self-Cleaning UVC Escalator Handrail

FIGURE 19
UVC Escalator Handrail Illustration

With permission of Schindler Group

The self-cleaning escalator handrail sterilizer uses UVC lights located inside the escalator that treat and sanitize high-touch handrail surfaces constantly while the escalators operate.

Effectiveness: A durable LED bulb focuses germ-destroying UVC light on the full width and sides of the plastic handrail as it passes to provide constant disinfection, providing consistent exposure to UVC sterilization as it operates.

Ease of application: This self-cleaning handrail sterilizer is both an easy upgrade for new installations and for retrofitting existing escalators. Compact handrail sterilizer modules are mounted internally to minimize the risk of UVC exposure. Many agencies have already implemented or are in the process of implementing such technology.

Capital cost: Since the technology associated with this measure involves retrofitting existing escalators, it is expected that it would be implemented with a moderate initial investment.

O&M cost impact: Incorporation of this measure would significantly reduce the need for on-site cleaning staff, so it has the potential to reduce O&M costs.

Equity: If this measure were implemented universally in a transit facility, all riders would benefit equally.

6.1.5 Display of cleaning logs

According to New York City's MTA, ridership plummeted by more than 90 percent at the peak of the COVID-19 pandemic [8]. In order to restore public confidence, it is important to convince customers that public transportation is safe and clean. One way is to display cleaning logs in transit facilities or on vehicles.

Effectiveness: This is an easy and basic solution that provides transparency about how often facilities or equipment are being cleaned.

Ease of application: Implementing such a measure can be done in a simple way by using display boards or electronic screens.

Capital cost: Since this measure could be an additive solution to any existing arrangement, it is expected that it could be implemented with low initial investment.

O&M cost impact: Since this simple measure is only displaying a cleaning schedule already being carried out, this would not add any additional O&M cost.

Equity: If this measure were implemented universally, all riders would benefit equally.

6.2 Vision for implementation in transit facilities

The following narrative provides a vision of a potential travel experience in the COVID-19 transit world that includes a combination of architectural and ventilation measures strategically implemented to provide a safe environment to patrons and transit employees. Some examples of industry-implemented measures are presented in Appendix A.

6.2.1 Vision for underground (enclosed) stations

6.2.1.1 Platforms

As a patron exits a subway train, clear signage guiding their disembarkation attracts their attention. Directional signage on the platform surface guides passenger flow away from embarking passengers to minimize direct encounters.

Approaching the stairs, escalators or elevators, patrons pass through a highly visible air purification system installed above the platform. Constant air flow with an added sanitizing agent (hydrogen peroxide [H_2O_2] or similar) is circulated, keeping the air purified and providing confidence that rider safety is enhanced through the quality of the air.

For those who choose to use the stairs, bold signage promoting one-way traffic is visible. Patrons feel safe grasping handrails treated with clearly marked antimicrobial or copper coatings. For patrons using escalators, escalator handrails with self-cleaning UVC devices installed continuously sanitize and disinfect the high-touch surface.

For patrons waiting on the platform, bold signage that prioritizes embarkation movement reminds passengers of the importance of maintaining a safe distance from one another. Vehicle density information on approaching trains is displayed on electronic screens, allowing riders to choose passenger cars with lower densities. Reconfigured station seating with transparent shields allows riders to isolate from one another via protective barriers.

PPE vending machines and hand sanitizing stations are installed throughout the station.

Figure 20 illustrates a station platform with possible architectural interventions.

FIGURE 20
Vision for Architectural Interventions in a Station Platform

6.2.1.2 Entrances

When patrons enter the station, they pass through an air purifying system installed at the entrance or gate that disinfects and sanitizes indoor air.

On approaching ticketing areas, directional and physical distancing signage guides passenger movement and promotes distancing requirements. Touch-free PPE and ticket vending machines are available to patrons, allowing them to minimize direct or indirect contact with surfaces.

Vehicle density information on approaching trains is displayed on electronic screens, allowing riders to choose to enter less-crowded passenger cars.

Throughout their journey, station and vehicle cleaning logs are clearly displayed to provide a high level of confidence in hygiene and to reassure riders about the safety of using public transportation.

Figure 21 illustrates a station entrance with possible architectural interventions. Appendix B shows additional platform and ticketing renderings.

FIGURE 21

Vision for Architectural Interventions in a Station Entrance

6.2.1.3 Fare gates

Patrons pass through touchless fare gates and do not need to touch traditional bars, turnstiles or gate mechanisms. Patrons pay their fares via their own contactless card or smartphone apps by tapping their card or phone on the gate reader. Riders are then admitted to the fare control zone.

While passing through the gate, riders experience purified air that neutralizes pathogens, blowing from overhead. The system disinfects contaminants in the air as well as on surfaces (patrons' clothing) and maintains a cleaner air quality. Directional signage on the floor guides patrons' movement and promotes one-way traffic, minimizing direct encounters with other patrons. **Figure 22** illustrates fare gates with possible architectural interventions. Appendix B has additional fare gate renderings.

FIGURE 22

Vision for Architectural Interventions at Fare Gates

6.2.1.4 Public spaces

Similar to other areas in the station, signs that remind riders to keep a safe distance apart can be seen throughout the public space. Patrons also notice reconfigured seating that allows for safe distancing. PPE vending machines and hand sanitizing stations are installed throughout the public space.

Looking at electronic screens that display passenger density information of approaching trains, riders will be able to predict and choose the vehicle car with less density.

Constant air flow, with an added sanitizing agent (hydrogen peroxide or similar), circulates and keeps the air purified, providing confidence and assurance about the quality and hygiene of the air.

6.2.1.5 Ancillary and service rooms

Providing safety and hygiene to transit employees is also important in promoting and restoring the use of public transportation to pre-pandemic levels.

In this vision for the future, air purification systems are also installed in ancillary spaces, using a sanitizing agent to keep the inside air purified. Increased air exchange rates are also implemented.

6.2.2 Vision for at-grade (open) stations

Similar to underground stations, directional and physical distancing signage, vehicle density information of arriving trains, station and vehicle cleaning logs, surface treatment with antimicrobial or copper coatings, etc. are provided throughout at-grade stations.

Studies have shown that COVID-19 transmission can be higher in confined indoor spaces. Therefore, more emphasis is placed on promoting physical distancing and disinfecting surface treatments rather than implementing HVAC interventions, since natural air is already provided at the at-grade platform, and air purifying systems are more beneficial to confined spaces.

6.2.3 Vision for transit rail vehicles

When riders get onboard transit rail vehicles, physical distancing signage installed on the vehicle’s floor reminds them to keep a safe distance from one another. Patrons sit on reconfigured seating treated with biocidal materials. One of the dynamic signs installed on the vehicle’s walls will show a log of the vehicle’s cleaning to ensure riders feel confident about the cleanliness and hygiene of the vehicle.

Increased air exchange and a newly installed air purification system in the vehicle provide riders with a much-improved indoor air quality during their journey.

6.2.4 Vision for buses

Similar to transit rail vehicles, high-touch surfaces on buses are treated with antimicrobial or copper coatings to minimize the spread of pathogens through surface contact.

A protective shield, such as a Plexiglass barrier, is installed around the driver’s seat to avoid direct contact between the driver and riders. Patrons are able to pay fares in advance using smartphone apps to avoid direct contact with the driver.

Increased air exchange rates, and a newly installed air purification system constantly running in the vehicle, mean riders experience much-improved indoor air quality during their journey.

Cleaning logs showing how often the bus is being cleaned are displayed, providing confidence to riders about safety and hygiene.

7. Ventilation interventions

> **NOTE:** The best-practice recommendations provided in this section are not prescriptive but are intended to provide information about possible approaches to disease control. Not every suggestion will be applicable to every pandemic outbreak, every community or every transit agency.

7.1 Air quality indicators in transit facilities and vehicles

The number of air changes (rate of replacing the entire volume of air within the space) with filtered and fresh outside air per hour and "age of the air" (reciprocal value of air changes) are critical factors in the control of air quality in transit facilities and vehicles.

All effective measures against the spread of airborne pathogens aim to achieve a sustained reduction of the viral load in the air we breathe. While low air velocities in the open environment are sufficient to reduce virus concentrations, mechanical, natural ventilation and air sanitization measures are valuable considerations for enclosed environments (station spaces, rail vehicles, buses, etc.).

Irrespective of whether infection occurs via droplets or aerosols, a key factor in becoming infected and the severity of infection is related to the critical number of bacteria or virus pathogens inhaled. The coronavirus concentration required for infection to take place is not yet clearly defined; however, one can reasonably assume that various virus concentrations have varying effects on people. Based on known infection pathways, it can be assumed that the number of viruses leading to an infection does not have to be part of a single breath. For example, to reach the critical number of viruses leading to an infection, it may take one deep breath with very high viral load, or it may take 15 breaths with smaller viral loads [3, 30].

Therefore, reduction of the pathogen load in the air we breathe via good ventilation is one of the most important elements in the control of personal safety against airborne viruses inside transit buildings, vehicles and underground facilities during a pandemic [3, 31].

However, even when dealing with enclosed environments with a high number of hourly air changes, there might be zones where the air is stagnant or circulating locally and is not replaced sufficiently by the ventilation system. These stagnant areas might have an increased number of pathogens in the air, so additional measures are required to improve passenger safety in the entire room or transit vehicle. Also, it is evident that the fresh air exchange rate should consider not only the volume of the enclosed space but also the location and number of occupants.

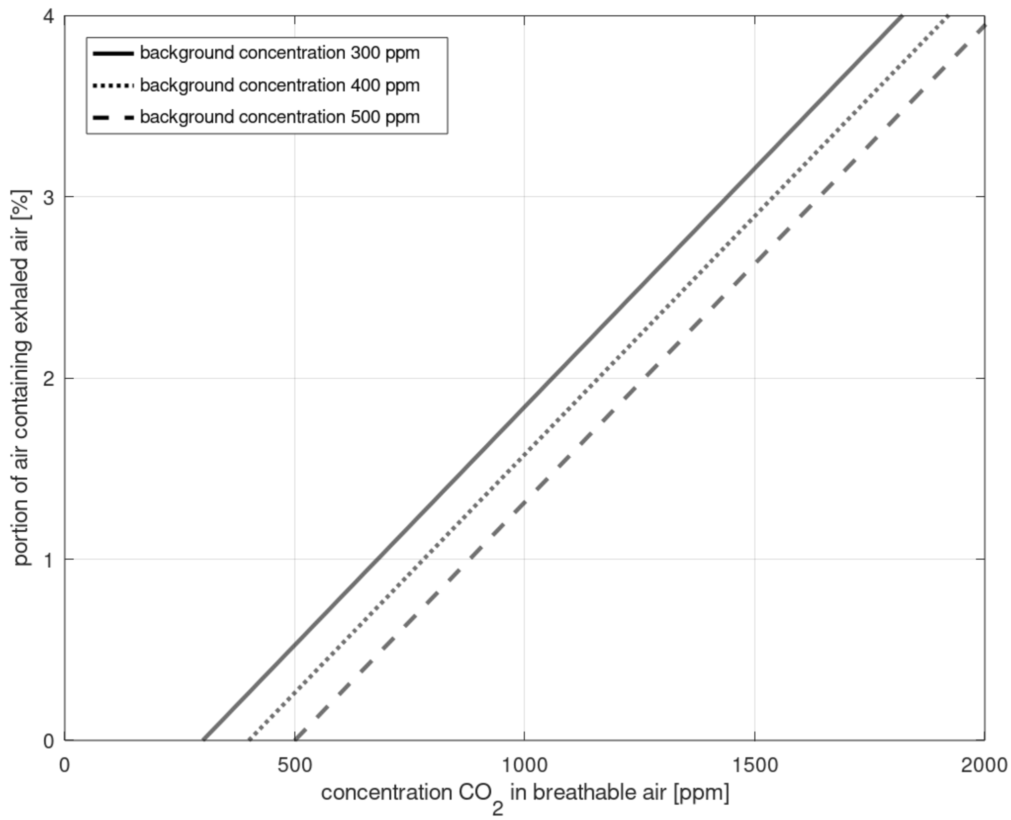
The carbon dioxide (CO_2) concentration in the air in enclosed environments is being considered as one of the key indicators of air quality. An increased risk of infection from airborne pathogens within enclosed rooms could be directly linked to increased CO_2 levels from human respiration [5]. Therefore, maintaining low CO_2 concentrations in enclosed rooms is a key indicator that the portion of the inhaled air that has been exhaled by another person in the room is low as well.

For ambient (outside) air the CO_2 content is approximately 300 to 500 ppm, depending on proximity to occupied areas, vehicular roadways, weather conditions (such as wind), seasons, and industrial and environmental impacts. For enclosed areas with a higher number of occupants, increased CO_2 concentrations are expected (meeting rooms, offices, waiting areas).

Generally, it can be assumed that for activities requiring lower levels of physical exertion (office work, sitting in waiting areas, or riding on a bus or train), a breathing rate of approximately 8 liters per minute (0.2825 cfm) of air is inhaled per person; in this case, the CO_2 production rate is approximately 0.3 liters per minute (0.0106 cfm [5]), which represents 3.8 percent of exhaled air.

Using a typical indoor CO_2 content of 1200 ppm with an ambient background CO_2 level of 400 ppm, it can be estimated that 1.8 percent of the air in a room has already been exhaled by occupants. This can be taken as a CO_2 concentration level that is satisfactory to the majority of people based on findings from ASHRAE [32]. In other words, for typical occupancies, approximately every 55th breath is made up entirely of exhaled air (see **Figure 23**).

FIGURE 23
Portion of Air Exhaled by Another Person



Concentration of CO_2 and portion of air that has been exhaled by another person for three different CO_2 concentration background levels (300, 400 and 500 ppm)

It is therefore evident that monitoring the CO_2 content of indoor air is a key indicator of air quality and may also be used to quantify the risk of pathogen spread and to determine when and where various mitigation measures should be considered (e.g., ventilation, air filtering, UV-light sanitization, use of sanitization agents, room evacuation [31]) such that the air quality could be maintained for higher occupancies to reduce the spread of airborne pathogens. In addition, risks of indoor airborne infection transmission can be reasonably quantified by measuring the air's CO_2 content (see **Figure 24**) and calculating the related concentration [5].

FIGURE 24
Typical Indoor Air CO_2 Measurement Devices

7.2 Ventilation interventions, including air sanitization

7.2.1 Increasing air exchange rates for enclosed public and staff service areas

Appropriate air exchange rates that maximize fresh outside air intake are important measures for controlling air quality and CO_2 levels in enclosed transit spaces, including transit vehicles, station patron areas, staff rooms and service areas. Studies have shown that enclosed spaces with ventilation systems that provide insufficient fresh air may lead to a ventilation-induced spread of infectious aerosols and droplets and thus pose a significant increase in infection risk to passengers and employees who are distanced from an infected person.

Experiences from rail studies in Germany show that for air exchange rates of about 7.5 per hour, there is no elevated risk of infection for train operating staff, even when employees are exposed to airborne pathogens in the cars for several hours per day [4]. By comparison, achievable air exchange rates for Washington D.C.'s Metro system are approximately 20 per hour and New York's subway system 18 per hour [33].

The ventilation system should be designed to maximize the proportion of fresh air within the transit vehicle. Typical rail transit vehicle air exchange rates provide approximately 25 to 30 percent fresh air intake. With such designs, positive effects of air exchanges with fresh air would be accessible to all passengers and transit employees; moreover, this method would be a superior way of decreasing the risks of airborne pathogen spread in comparison with other ventilation methods.

Therefore, the air exchange rate with fresh air is the key factor for planning transit ventilation (HVAC) and thermal comfort for new transit stations and vehicles, as well as for refurbishment of existing stations. Patron density–dependent air flow interventions might be triggered, for example, by the monitored CO_2 concentration in the air.

The proportion of fresh air introduced by active HVAC systems to transit facilities and vehicles should be based on consideration of various boundary conditions, such as summer or winter situation, as well as facility configuration (tunnel vs. at-grade operation) and the geographic climate zone (Texas vs. Washington state).

Regardless of the type of measured value or measurement technology, these measurements are used to control the ventilation equipment (fans start/stop, damper control). Closed control loops should be preferred for the flexible use of the ventilation equipment in various scenarios.

Effectiveness: Use of ventilation via increasing fresh air exchanges is the key factor for patron and employee COVID-19 safety. Air quality control via monitoring CO_2 concentration with approved technology is highly effective.

Ease of application: This measure is easily applied in both cars and stations; in most cases, tunnel and station ventilation is available. A control concept is required (when to start, how long, which flow rate), along with integration into the HVAC concept. This measure will probably require increased air flow rates, which might be possible to implement via optimized fan technology.

Capital cost: Costs for ventilation improvement are considered to be low.

O&M cost impact: The incorporation of this measure would increase maintenance efforts for ventilation systems.

Equity: If this measure were implemented universally, all riders would benefit equally.

7.2.2 Filtration methods for HVAC

A key factor in maintaining or improving the air quality in transit facilities is the integration of effective air filter elements into transit station and vehicle HVAC systems. For ventilation systems with limited outside air supply, filtration systems are important to ensure the quality of air that has been recirculated from the space. For closed-loop air-circulation systems without fresh air supply, these filter systems are essential: They help avoid propagation of airborne particles and pathogens through the ventilation/air conditioning system.

Some of the most effective filters for practical use are high-efficiency particulate air (HEPA) filters, which are implemented on airplanes for their capabilities in increasing cabin air quality and reducing airborne particle transmission [6].

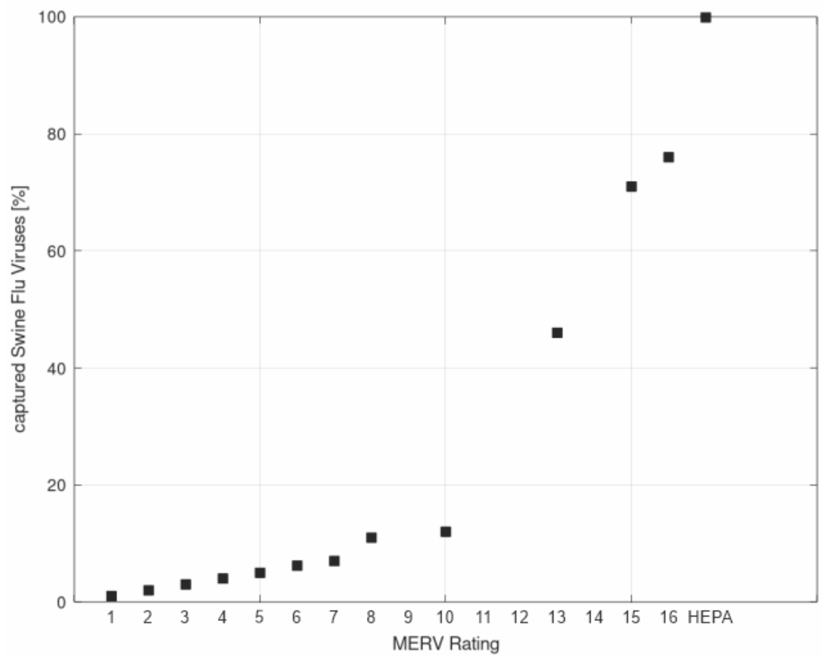
In contrast with the ambient air on airplanes, the ambient air of public transit facilities and vehicles, especially those operating underground or within enclosed facilities, contains higher levels of particulate matter from underground equipment and abrasion (wheel-rail, third rail, tire-road [35]), pollen, fine dust, and environmental dust. Consistent with the building industry, Minimum Efficiency Reporting Value (MERV) filters with lower effective ratings than HEPA filters are used. MERV filters are available with different ratings indicating the particle size filter efficiency.

Experience with swine flu viruses [35] indicates that significant virus filter efficiency can be achieved with filter systems with ratings higher than MERV 14 (see **Figure 25**). However, even lower filter ratings are helpful, specifically when used with other measures (e.g., high fresh air exchange rates, additional sanitization with UV light, etc.).

Electrical filters function on the basis of dielectric polarization. By creating high-voltage differences across ducted air paths, the electrical filter has the ability to “trap” particles such as dust, fumes, viruses, bacteria, pollen, etc., and are used for enclosed-room transit applications.

FIGURE 25

Captured Swine Flu Viruses in Relation to MERV Rating and HEPA Filter



The major drawbacks of any filtering techniques are as follows:

- A need for maintenance that requires proper staffing for visual inspections, cleaning and/or replacing the filters
- Increased electrical power consumptions due to higher aerodynamic resistance caused by the filters in the ventilation path

For the reasons above, major European rail operators (e.g., Deutsche Bahn in Germany) do not generally use high-performance HEPA filter technologies for their standard rolling stock [4].

Effectiveness: HEPA filters are efficient but impractical in enclosed transit environments (rail) due to elevated risks of clogging with rail dust, which requires a high level of maintenance. Lower-rated MERV filters are useful to increase air quality generally (e.g., filtering rail dust), but do not stop the same number of aerosols as HEPA filters.

Ease of application: Filters can be readily integrated into most HVAC systems. However, they will increase the probability of ventilation fan failures (and need for replacement) due to increased pressure losses resulting from rail dust clogging.

Capital cost: Costs for ventilation improvements including installation or refurbishment are considered low. Increase in power consumption is negligible.

O&M cost impact: This measure would increase maintenance costs.

Equity: If this measure were implemented universally, all riders would benefit equally.

7.2.3 Air purification via photohydroionization and hydrogen peroxide

A possible effective measure in terms of air sanitation in transit facilities (enclosed spaces) and vehicles is hydrogen peroxide. This measure requires further research and would be used in conjunction with ventilation measures for purposes of improving air quality and arresting the spread of airborne viral pathogens such as COVID-19. Testing for COVID-19 is still in progress as of August 2020.

Hydrogen peroxide is a substance found in nature and occurs in very low concentrations in the outside air. For more than 100 years hydrogen peroxide has been used in the medical field for disinfection, in daily life for cleaning, and in cosmetic products in liquid form or as an additive.

The National Institute for Occupational Safety and Health (NIOSH) identifies the current OSHA permissible exposure limit (PEL) of 1 ppm for hydrogen peroxide, whereas the typical outdoor level is approximately 0.02 ppm. The short exposure tolerance is presently unknown but is probably higher than 75 ppm [36]. Therefore, the limit value considered toward air sanitation application can in all probability be considered safe for the public, especially in the case of short-term exposure. Decades of experience from existing applications in the food industry and hospitals show no additional health risks to exposed people.

Technologically, the production of hydrogen peroxide for the purification of air is carried out via a photohydroionization (PHI) cell. A UV light source is used in conjunction with a special surface to produce hydrogen peroxide from the moisture in the air using prevailing water and oxygen molecules. Over the past 20 years, the use of PHI technology has spread worldwide and has achieved a solid track record.

The use of hydrogen peroxide–generating technology was taken into consideration in the computational fluid dynamics (CFD) analysis of a generic subway station discussed in Section 7.3. In practice, airborne hydrogen peroxide, in the concentration range of 0.02 to 0.05 ppm, is used as a sanitizer that is released into the air flow. This sanitizing technology, among others, is already in use in the food, leisure and health industries and might have real potential for air purification purposes in transit facilities, subject to further research and development of standardized testing procedures. The CFD analysis in Section 7.3 assumes that hydrogen peroxide can rapidly inactivate airborne viral pathogens. The analysis results are considered representative of various agent-based air sanitizing techniques, in which fast-acting molecules of the air sanitizing agent are rapidly mixed with air on a molecular level and are capable of neutralizing the viral pathogen swiftly.

Appendix C presents a methodology for standardized testing in transit cars where an air purification system using hydrogen peroxide has been implemented, along with possible procedures for testing.

Effectiveness: Technology is used in other industries, including hospitals.

Ease of application: This measure requires a simple mixture of sanitization molecules with air flow and can be integrated into most HVAC systems. It also can be installed as a standalone system.

Capital cost: This measure would require a moderate investment.

O&M cost impact: The incorporation of this measure would increase maintenance efforts moderately.

Equity: If this measure were implemented universally, all riders would benefit equally.

7.2.4 Ionization

Air ionizers typically use high voltages to charge air molecules in order to generate positive and negative ions. Previous studies in British hospitals have shown that positive and negative ions generated and distributed by the hospital air conditioning system can deactivate viruses [37].

Even though the development of air ionizers accelerated during previous pandemics (including SARS, from 2002 to 2004) standardization of this technology has not yet been established. Therefore, the integration of such measures into HVAC systems needs careful evaluation and testing. Passive ionization devices without fans impact only the field near the ionizer. These units can be integrated into ventilation ducts or installed when refurbishing existing air conditioning systems. In contrast, active devices with fans can help to swirl and propagate the ions throughout the air. These units can be installed in offices or stations (e.g., in waiting areas, along the pedestrian path) when other systems cannot be used.

At present the lack of standardization and efficiency testing studies are major drawbacks of these systems, even though positive experiences are well-documented.

Effectiveness: This measure is a simple mixture of ionized molecules with air flow, which is an efficient and approved technology in other industries, including hospitals.

Ease of application: Ionizers could be integrated into most HVAC systems. They also be installed as a standalone system.

Capital cost: It is expected that this measure could be implemented with a moderate investment.

O&M cost impact: The incorporation of this measure would increase maintenance efforts moderately.

Equity: If this measure were implemented universally, all riders would benefit equally.

7.2.5 UV light

UV light is known to kill viruses and bacteria by damaging the biological cells on a molecular level (damage of DNA). The intensity and duration of UV-light exposure are the key parameters of the efficiency of this measure. The key characteristics of UV light solutions:

- They cannot be used close to patrons and employees due to the impact on human cells.
- When used for disinfecting rooms (without occupants), an extended period of exposure (from several minutes to hours) is required, depending on the intensity.
- UV light has a short range (decreasing intensity from the source) and requires UV lamps/sources to be moved around for the complete sanitization of rooms.
- Shadowed areas are not sanitized.
- Ventilation in cars or stations typically requires high-volume flow rates, where the impact time of UV light sources in the ducts is short due to air speed.

Effectiveness: UV light can be an additional measure for air and surface sanitization. However, due to slow impact times and short-range capabilities, it might be part of the ventilation equipment before air is supplied to offices, cars or stations. Nevertheless, such systems can be a great second measure (e.g., filtering and UV light application in air ducts).

Ease of application: Integration into car HVAC systems would require each car to be equipped and faces the obstacle of limited space. Integration in building HVAC systems would be rather simple. UV light treatment is not possible when patrons or staff are present. New or refurbished stations could include integration of UV lamps in architectural/lighting concepts.

Capital cost: Costs for adequate UV sources are moderate. Integration into railcar or bus HVAC systems would lead to relevant investments.

O&M cost impact: The incorporation of this measure would increase maintenance efforts for vent systems slightly. When using for disinfecting rooms, staffing costs would be required.

Equity: If this measure were implemented, all riders would benefit equally.

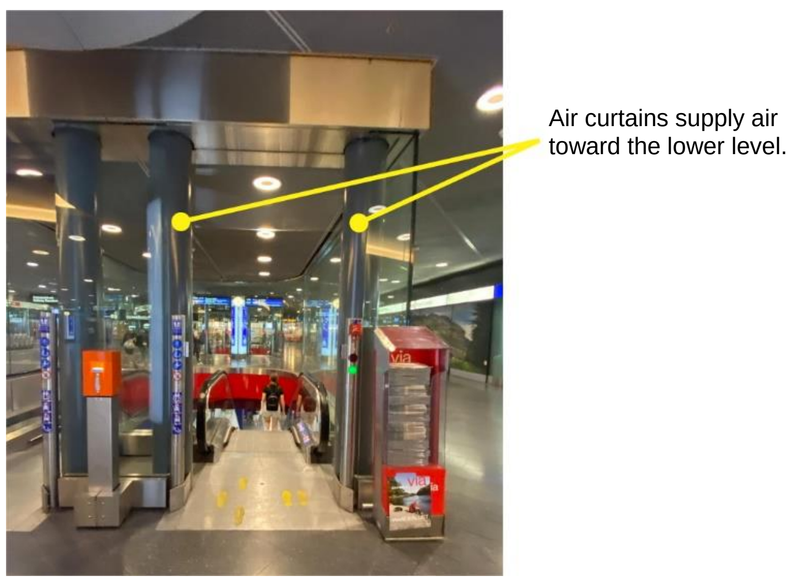
7.2.6 Air sanitization at portals in stations and terminals

Irrespective of an overarching need for proper ventilation and cleanliness protocols within enclosed transit spaces, including bus stops and stations, special sanitization measures could be of great value during and after the pandemic for areas with higher passenger density. This applies, for example, to the following:

- turnstiles for entering or leaving the station
- ticketing points
- commercial zones
- waiting areas
- escalators and/or stairs

Fare gates with a sanitization portal, with hydrogen peroxide generated in the upper box, are shown in **Figure 26**. Particularly noteworthy are air sanitation portals at the upper landings of escalators leading from the mezzanine level to the track or platform level.

FIGURE 26
Vertical Air Curtain at Upper Landing of Escalator Between Mezzanine and Track Levels



Airport Zurich

The advantage of installation at that position (upper escalator landing before reaching track level) is that patrons can stand close together on both sides (upper landing and lower landing), as any pathogens will have effectively been rendered harmless. In addition, due to the piston effect from the adjacent tunnels (track level) the direction of air flow is usually from the upper level toward the platform. Hydrogen peroxide will therefore be transported toward the platform, helping to sanitize a wide area.

7.2.7 Air sanitization in staff service rooms

Air sanitization for transit staff rooms should be implemented in the following cases:

- If appropriate ventilation measures cannot be applied
- For rooms with high density of staff or staff and visitors (e.g., canteen entrances)
- For areas with normal density of staff but involving intense physical work involving sweating and/or heavy breathing during work execution

It is recommended, however, that an appropriate ventilation solution including outside air exchanges be considered and established prior to considering air sanitization solutions whenever practical.

7.2.8 Air sanitization in rail vehicles and buses

Air sanitization in rail vehicles and buses should be considered as follows:

- If there is a very high rider density (crush-load) anticipated on a regular basis
- On commuter or other travel routes where travel time is extended (e.g., more than 30 minutes between stops) and if sufficient ventilation measures cannot be applied

When air sanitization appears to be the most efficient method to control air quality and provide a safe travel environment, it is strongly recommended that a simple engineering assessment be implemented to check first whether a ventilation solution would work prior to deciding to implement air sanitization measures.

Effectiveness: Use of sanitization measures is considered effective. This measure does not only work locally, but within a certain working area, depending on the prevailing air flow conditions.

Ease of application: This measure requires moderate effort for integration into existing HVAC systems.

Capital cost: Costs for air sanitization measures are considered moderate.

O&M cost impact: Incorporation of this measure will slightly increase maintenance and operating costs, as the system requires visual inspection and cleaning.

Equity: If this measure were implemented universally, all riders would benefit equally.

7.3 Computational fluid dynamics/3D numerical simulations

To evaluate airborne pathogen spread in transit vehicles, a number of CFD analyses were implemented to simulate air flow patterns provided by HVAC systems in a generic subway car. Aerosol and droplet pathogen dispersal was simulated in the event of a rider coughing, with and without a face mask. The objective was identification of local zones within the car where the air might be stalled; such “air pockets” tend to accumulate pathogens in the air or on surfaces over time. The aerial pathogen dispersal simulations inside the car would reveal quite reliable locations of pathogen particles and their accumulation over a period of time for the assumed vehicle and its specific HVAC system.

In addition, the CFD analysis of a typical subway station was carried out to examine the effects of continuous air sanitization using low levels of a sanitizing agent (e.g., hydrogen peroxide). It is noted that a sanitizing agent could also be implemented in transit vehicles as an effective way of reducing the pathogen load; however, it has been observed that the number of required air exchanges (as a method of air quality control) are generally easier to attain in transit vehicles compared with those at stations, especially if stations are “grandfathered.”

Simcenter STAR-CCM+, a commercial 3D CFD software, was used to identify predominant factors present for airborne pathogen spread. Other commercial CFD software packages currently available include ANSYS, OpenFOAM and AutodeskCFD. Simcenter STAR-CCM+ is an industry-leading CFD software package that facilitates 3D transient simulation of almost any engineering problem involving the flow of liquids, gases or a combination of both, together with all associated physics (e.g., thermodynamics, fluid-structure interaction and rail aerodynamics). The software application was configured with industry standard conventions for CFD analysis of this scenario with the following features:

- domain meshing to capture flow field conditions
- species diffusion models
- droplet aerodynamic forces
- momentum flux introduction
- nominal thermal effects for buoyant flow conditions

7.3.1 Typical transit station, railcar and bus ventilation

Stations and vehicles vary across transit systems, but many share similar features, including mechanical ventilation arrangements. In order to simplify the analysis, representative railcar/bus and transit station geometries and layouts were used for modeling purposes to demonstrate generally expected performance of the mechanical ventilation–based airflows and potential air sanitization effect on the spread of airborne pathogens.

7.3.1.1 Typical railcar

HVAC air distribution components are located on the ceiling of the car. Air supply vents are located along the longitudinal axis of the car, providing filtered and conditioned air from the ceiling above the passengers, increasing passenger thermal comfort. Exhaust air openings are located at either end of the generic car, as shown in **Figure 27** and **Figure 28**.

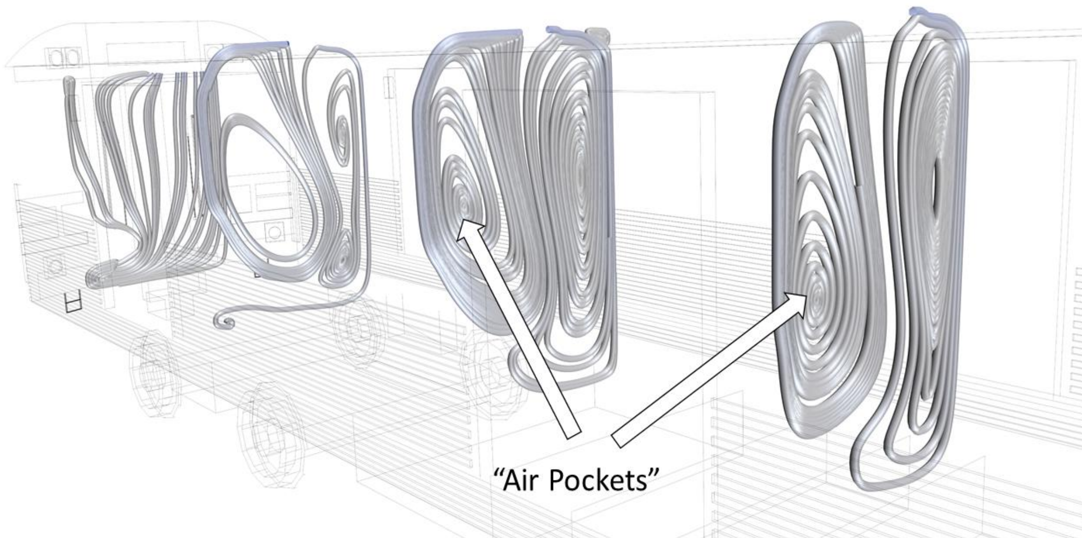
FIGURE 27
Air Supply (Blue Arrows)

FIGURE 28
Exhaust Air (Red Arrows)

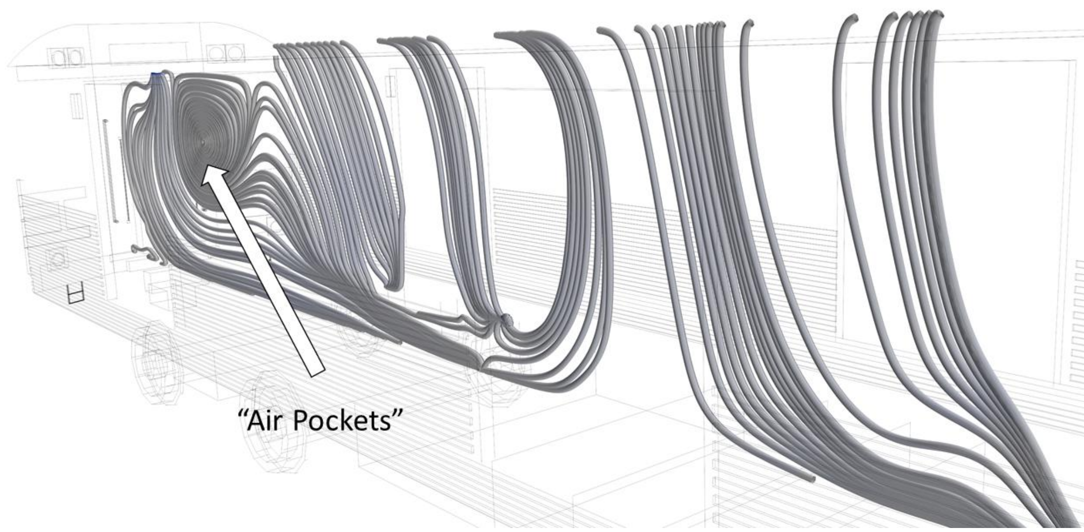
Figure 27 and **Figure 28** show the airflow at the supply air vents inside a typical subway railcar. Air is supplied overhead (supply air vents) on the car ceiling and returned near the car ends (return air vents).

To achieve thermal comfort, the HVAC system circulates the cold airflow away from passengers to minimize those directly exposed. The drawback of this system, especially in a pandemic situation, is that the supply air is recirculated, and its mixing with the fresh air in the car is limited. Some railcars include separate fresh air grilles located on the outside of the carbody that are sized to allow a portion (percentage varies by railcar manufacturer) of fresh outside air to mix into the return air duct. Also, stagnant "air pockets" can be identified where recirculated air gets "trapped," and minimal air exchange, if any, is observed (see **Figure 29**). Pathogen particle concentrations in these areas are likely to be higher on average, and the fresh air exchange rates in those zones differ (locally) from the given car fresh air exchange rate, which is a global number.

FIGURE 29
CFD Analyses of a Subway Car



Airflow visualization using streamlines (areas with locally reduced air exchange rates are indicated as air pockets in the seating areas)



Airflow visualization using streamlines (areas with locally reduced air exchange rates are indicated as air pockets in the seating at the end of the car)

7.3.1.2 Generic rail/subway car CFD simulations

As noted, CFD simulation was carried out for a generic rail/subway car that included the car's HVAC system, as well as passengers with and without face masks. These transient analyses of a multicomponent gas flow are capable of accurately capturing pathogen particle (droplets, aerosol) dispersion. The numerical 3D simulations consider aerodynamic drag as a function of particle size and assume that droplets remain on surfaces upon contact.

The CFD results (**Figure 30** and **Figure 31**) visualize the particle and droplet spread where a standing person, without a mask, coughs. The pathogen droplets are immediately accelerated by the moving air, due to aerodynamic drag, and are carried through the interior of the car. The analysis simulates two minutes of real time (a typical duration between two subway stations) and shows that smaller particles remain in the air the entire time. The HVAC system and its inlets and outlets, connected with car ventilation ducts, disperse the droplets throughout the entire car. Due to the size of the outlet ports and their location, the droplets remain in the air long enough to reach almost every single person inside the car, potentially spreading pathogens and infecting passengers, even those who are distanced from the source. Given the number of droplets remaining in the air after a two-minute simulation, one can assume that the pathogen particles would remain active in the air for a long time.

FIGURE 30
Airborne Pathogen Spread with and Without a Face Mask at the Moment of Cough

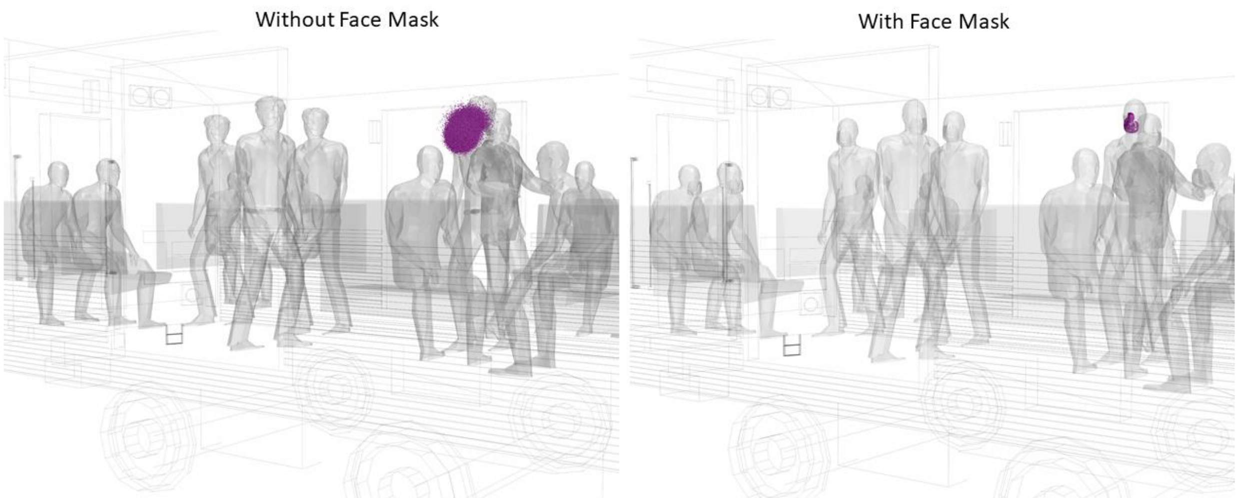
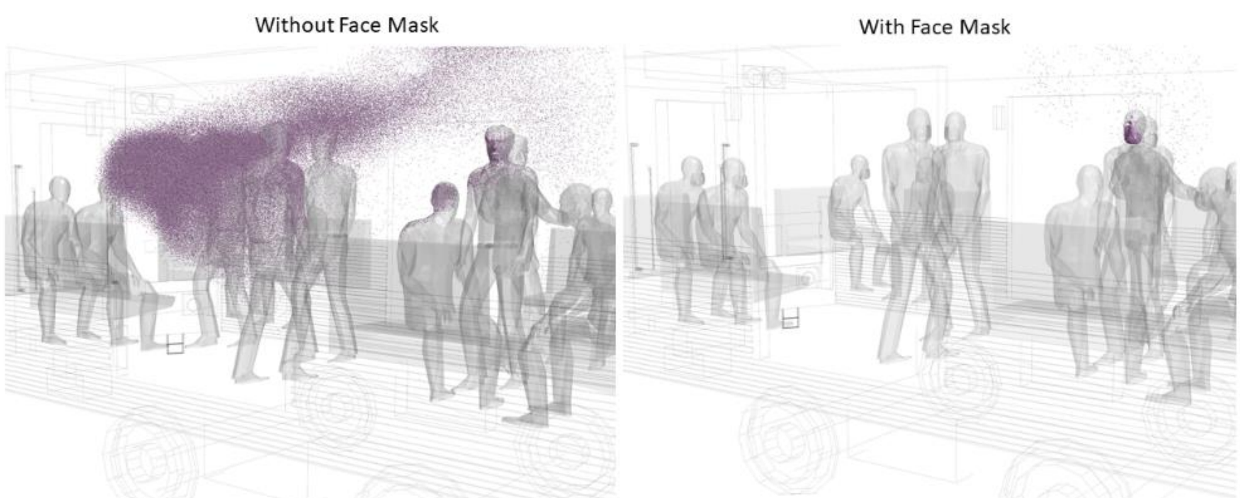


FIGURE 31
Airborne Pathogen Spread with and Without a Face Mask, 5 Seconds After Cough



The second CFD analysis (see **Figure 32** and **Figure 33**) simulates the situation where a standing person with a face mask coughs. All the riders in the car are modeled with a face mask as this is required by most transit agencies. The CFD analysis reveals that most of the large airborne pathogen particles remain attached to the mask after the cough. The rest of the particles are dispersed from the person's face with a very low velocity compared with the case where a person coughs without a face mask. This, in turn, reduces the spread of pathogen particles along the car. Small pathogen particles would remain in the air as they are carried along by aerodynamic forces; however, it is unclear if their density and size are sufficient to infect other passengers. This localized particle path additionally underlines the necessity for efficient air extraction along the car and above the passengers. Since all the passengers in the car are wearing face masks, the chance for possible infection likely limited.

The figures below give detailed insight into comparative analysis between the two analyzed situations.

FIGURE 32
Airborne Pathogen Spread with and Without a Face Mask, 20 Seconds After Cough

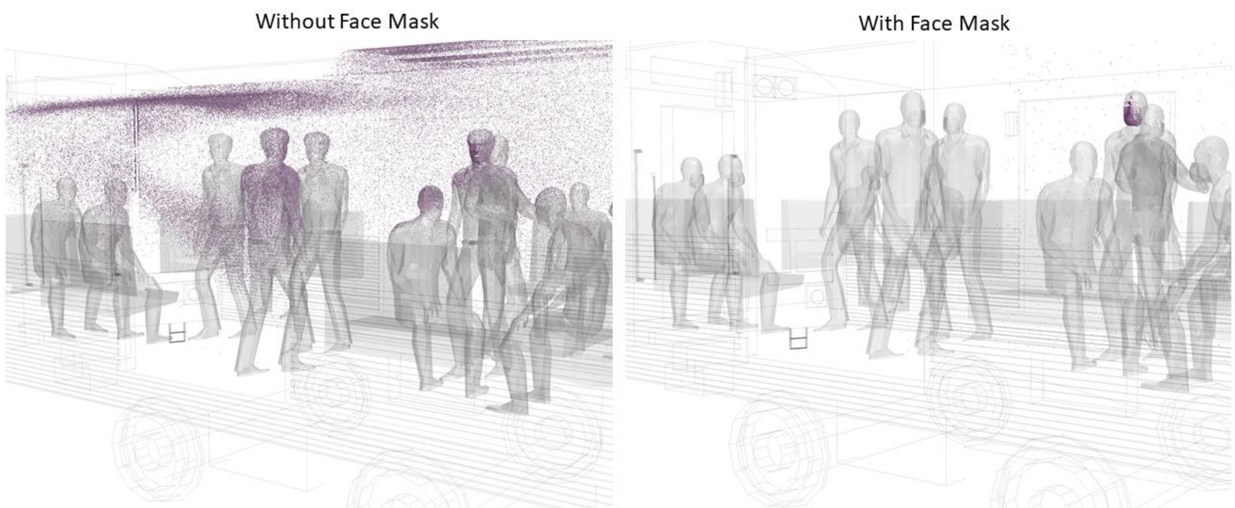
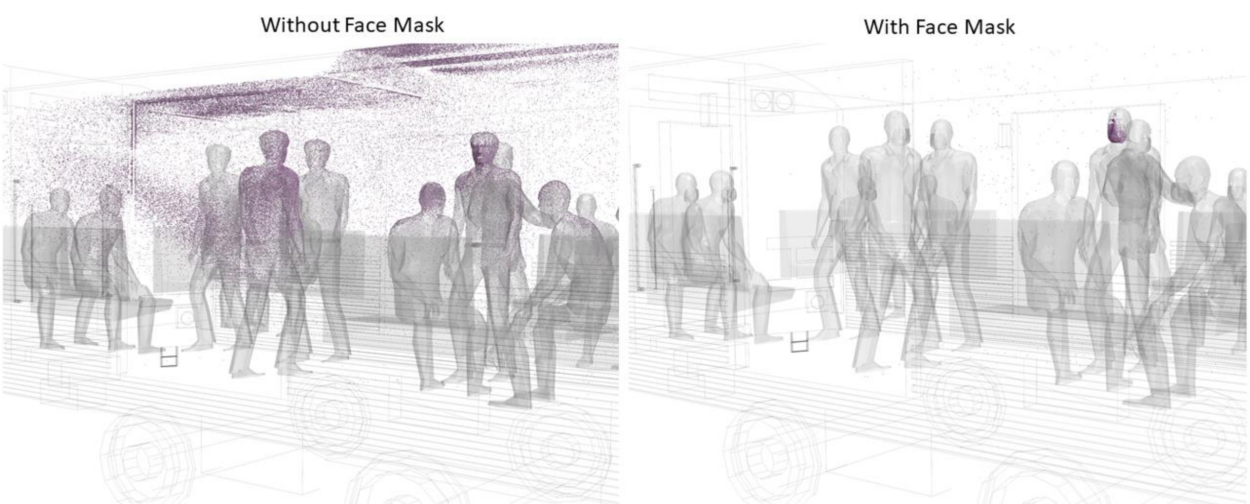


FIGURE 33
Airborne Pathogen Spread with and Without a Face Mask, 40 Seconds After Cough



Similar simulations could be used in the future to model spatial distribution of an air sanitizer introduced into a HVAC system, its mixing with the air and the air pathogens, and the pathogen particles' neutralization ("deactivation") by the air sanitizing agent. This is the subject of a future study pending credible research data regarding sanitizing agents' efficiency and their safe concentrations.

7.3.1.3 Generic transit station CFD simulations

In contrast with vehicles, aerodynamic and thermodynamic considerations of underground stations are much more complex. Underground stations are often connected by tunnels; the air in the tunnels is set in motion by the so-called piston effect of the moving trains. As a result, air is transported from the tunnel to the station or from the station into the tunnel. Therefore, it is almost impossible to control the air flow rates at a station's platform level or at platform levels of all other adjacent stations. Passenger circulation routes in a station could also be exposed to different prevailing flow conditions, giving them different prevailing air quality. In addition, a stack (chimney) effect plays an important role on air movement. This effect leads to different boundary conditions in winter or summer and might lead to multiple reversals of the air flow direction daily. All these conditions in the station effect the transportation of pathogen particles. The generally complex condition might be different when PSDs are used to separate tunnel environments from stations.

New stations could be designed for appropriate ventilation and fresh air exchanges to control pathogen loads in the air. Existing stations, often grandfathered, traditionally have limited station ventilation and consequently air circulation, due to the stack and the piston effect. A potential strategy to rectify the problem of low air circulation, using CFD simulations, is to supply the transit station with safe amounts of air sanitizer (hydrogen peroxide or another agent) via commercially available units. In the case of hydrogen peroxide, units typically provide 0.02 to 0.05 ppm of this sanitizing agent, which is far below the safety limits for maximum concentration recommended by OSHA standards.

The CFD analysis considers flow from three horizontally located units with volume flow of 18,000 cfm and three smaller, vertically located units with volume flow of 8000 cfm. The mass fraction of hydrogen peroxide is set to 0.02 ppm on the inlet surfaces.

The units are strategically located in areas where passengers spend most of their time while waiting. Typically, these are the areas in the vicinity of fare gates, stairs, escalators, platforms or other locations where passengers stand close together. The airflow from the units may be designed in such a way as to form a vertical air curtain that sanitizes the passengers as they pass through. As an example, in this CFD analysis, the three smaller units and one horizontal unit are located on the top of the escalators and stairs dispersing hydrogen peroxide toward the lower level (see **Figure 34** and **Figure 35**). This way, passengers remain surrounded by the sanitizing agent as they travel to the platform on the lower level. Additional horizontal units are located above the platform, where a higher concentration of passengers is expected.

FIGURE 34
CAD Representation of Subway Station Including Mezzanine and Air Sanitizer Dispensers

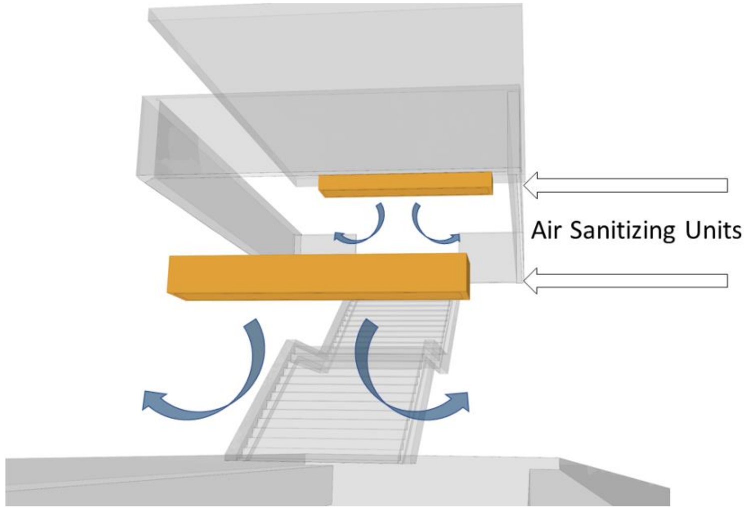
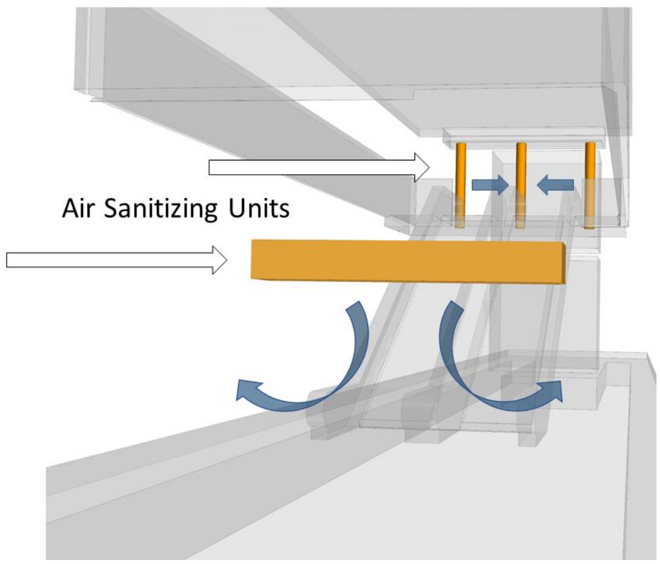


FIGURE 35
CAD Representation of Subway Station with Two Types of Air Sanitizer Dispensers



The CFD analysis (**Figure 36** and **Figure 37**) shows that the supply units of a commercially available size may provide sufficient amounts of hydrogen peroxide even for facilities with large volumes of air, such as underground transit stations. Strategic locations of these units, possibly determined by a CFD analysis, may provide uniform distribution and optimal levels of hydrogen peroxide throughout the whole station.

FIGURE 36
Air Sanitizer Visualization in a Typical Transit Station

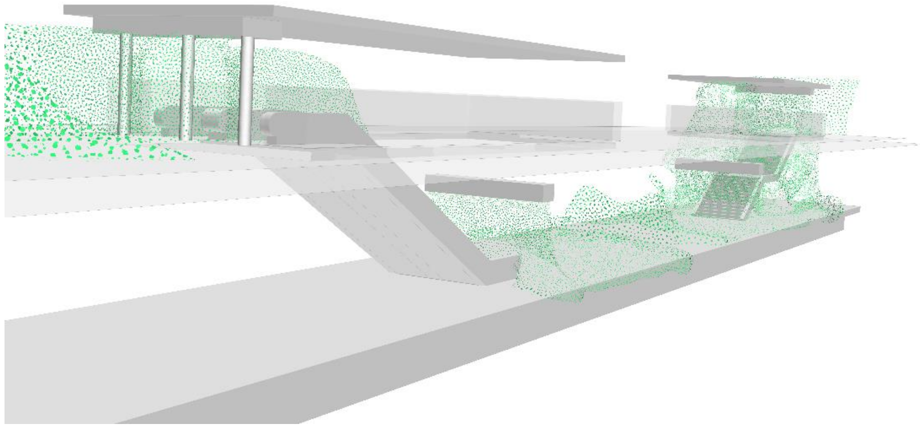
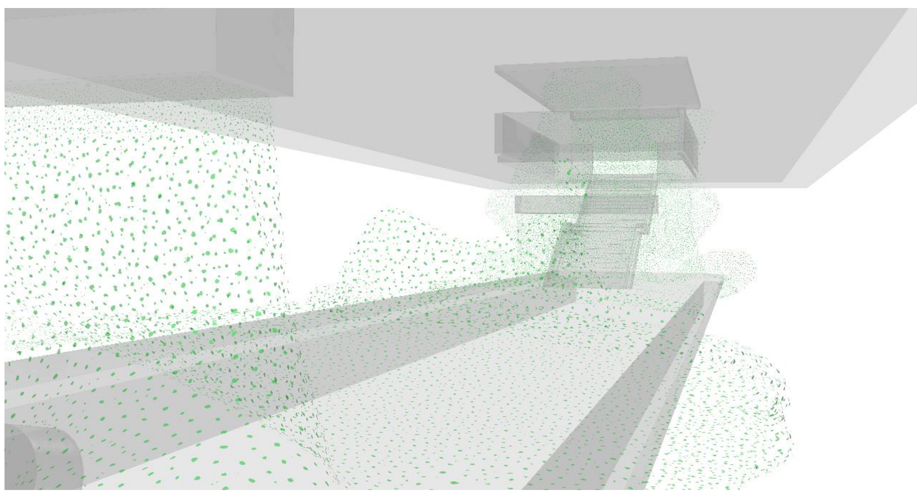


FIGURE 37
Air Sanitizer Visualization in a Typical Transit Station (Close-Up)



7.3.2 Conclusions from 3D simulations and potential implementation

The locations of airborne pathogen particles are functions of aerodynamic and thermodynamic forces acting on the particles as they are released in the air. Larger droplets tend to stick to adjacent surfaces quickly, while smaller particles remain in the air. The pathogens remain in the air until they are extracted from a car by the HVAC system, are inhaled, or attach to a car surface or a person.

Current HVAC systems in transit cars disperse the pathogen particles in a disordered way, helping pathogens to spread throughout the interior of the vehicle. The pathogen particles may therefore reach all the passengers in the car depending on the duration of the subway ride.

The effect of wearing a face mask significantly reduces the pathogen spread. The majority of pathogen particles are retained by the face mask, and the velocities and sizes of particles are greatly reduced. Therefore, currently required minimum spacing of 6 ft between the adjacent passengers could be reconsidered and closer spacing proposed, especially if the interior of the car is ventilated properly (with sufficient air exchanges) or if a safe dosage of air sanitizer is introduced and able to act efficiently with pathogen particles at a molecular level to rapidly neutralize them. Also, repositioning of the air outlet ports may reduce the amounts of pathogens in the car.

Reduction of airborne pathogens within enclosed station areas can also be achieved through airborne sanitizing agents and/or fresh air changes. It appears that commercially available hydrogen peroxide units, for example, seem capable of providing sufficient amounts of the agent that are below the safety limits recommended by OSHA standards. Draft vent flows generated by train movement help the mixing and dispersion of air sanitizing agent in the stations.

Conclusions made within this paper are based on generic enclosed space conditions for transit vehicles and fixed public station access infrastructure. The results presented indicate general trends and identify significant features within transit systems that would impact COVID-19 transmission. For this reason, many parameters cannot be quantified. More detailed evaluation for specific enclosed space geometry and ventilation configurations and flow quantities would be required to provide quantifiable results.

8. Planning tools

> **NOTE:** The best-practice recommendations provided in this section are not prescriptive but are intended to provide information about possible approaches to disease control. Not every suggestion will be applicable to every pandemic outbreak, every community or every transit agency.

8.1 Evaluation matrices

Appendix D presents a series of matrices that compile relative evaluations of available individual interventions that have been used nationally and internationally for reducing pathogen spread and purifying air. Matrices were developed for the following types of transit facilities:

- underground (enclosed) stations
- at-grade (open) stations
- transit rail vehicles
- buses

The various types of available architectural and ventilation intervention measures were evaluated for each type of transit facility for the following five criteria:

- **Effectiveness:** Rated as high, moderate or low
- **Ease of application:** Rated as high, moderate or low
- **Capital investment (initial cost):** Rated as low, moderate or high
- **Lowering of operations and maintenance cost:** Rated as to whether or not the measure resulted in lowering long-term operation and maintenance costs (also, initial capital costs might be offset by lower operation and maintenance cost later; this would likely benefit the owner's operating efficiency).
- **Achieving equity:** Rated as to whether the measure resulted in all riders and employees being treated in a fair and unbiased way while providing universal access.

An overall rating considering all criteria was also developed for each measure.

All evaluations in Appendix D are qualitative. No weightings were applied to the various criteria, although some criteria might be considered more important, or more practical, than others to various owners and operators. It is expected that transit agencies will review the matrices and apply weightings that reflect the relative importance or criticality of each criteria with respect to their specific goals and resources.

8.2 Decision trees

Appendix E presents two decision trees to be used as an evaluation tool for the following types of transit facilities:

- underground (enclosed) stations
- transit rail vehicles and buses

These decision trees represent a suggested methodology and are intended as a starting point/framework for transit agencies to take stock of their facilities. By answering a series of prioritized yes/no questions, agencies can determine the available measures that would likely be most suitable for promoting pandemic-safe mobility for their patrons and employees.

These decision trees can be used to assist in initiating the process to find the most appropriate ways to deliver critical and healthy transit service to patrons and employees.

9. Recommendations

Based on experience, published research and studies, and the results of architectural and ventilation evaluations including 3D modeling and CFD simulations, it appears that two key factors have emerged in terms of controlling the pathogen (and viral) load toward safety of transit riders and employees:

- air quality
- passenger density

The air quality of any enclosed transit space directly depends on fresh air supply and exchange rates. The measurement of the CO_2 in the air is a good indicator of air exhaled by other people, including those infected with a pathogen. The greater the portion of CO_2 in the air, the greater the risk of infection.

The number of passengers may significantly affect the air quality and therefore the number of required fresh air exchange rates in enclosed rooms especially during the pandemic. For that reason, passenger density plays a significant role, and measures should be taken to control numbers in the case of a pandemic. However, if acceptable air quality—accompanied by sufficient fresh air exchanges—is provided in enclosed transit rooms, the requirements for passenger density (physical distancing) might be relaxed, especially when protective measures (masks, shields, gloves, good personal hygiene, etc., as noted in Section 5) are implemented.

For rider and employee safety, CO_2 concentrations in enclosed spaces should be monitored and limited to approximately 1000 ppm, which is considered as harmless to health [38] and is understood as reasonable to reduce the risk of infection due to airborne viruses [5].

The number of air exchanges with fresh air can depend on the CO_2 concentrations and therefore on the number of people and the enclosed volume. Nevertheless, it was found that for 7.5 fresh air changes per hour, the average infection rate for transit employees (exposed over hours) was less than for the rest of the population [4]. However, for commuter trains, fresh air exchange rates up to 20 per hour are achievable. According to the current understanding of the virus spread and various experiences, it is recommended to use high air exchange rates ($\geq$ 7.5 per hour), even though this is not required for thermal comfort. This recommendation could be used until confirmed by various transit owners and operators based on their own systems and safety circumstances, as well as input from health authorities.

If acceptable air quality cannot be achieved, then greater passenger densities increase the risks of infection by pathogen aerosols or droplets. Droplets are more infectious than aerosols and are larger in size; however, both comprise the risks. Droplets are emitted mainly by coughing, sneezing, loud speaking, singing and heavy breathing. To mitigate the above infection risks, appropriate architectural measures could be implemented to reduce passenger densities; also, air sanitizing measures could be deployed to neutralize infectious aerosols and/or droplets in the interest of safety of transit riders and employees.

There are various measures identified throughout this white paper and in evaluation matrices (Appendix D) that would reduce the pathogen load on high-touch surfaces or are geared toward reduction of densities using information technology that, for instance, allows riders to make safer choices in selecting a more sparsely occupied vehicle for their journey.

As each facility is unique, the measures presented herein are a starting point and a suggested methodology toward the goal of safer and healthier transit for both new and existing transit stations, railcars and buses. Each facility or vehicle requires unique assessment guided by the attached decision trees and matrices that should be used as tools to assist agencies in their safety decisions.

10. Next steps

1. Periodic updates to this white paper should initially occur after a six-month period following publication, and then on a yearly basis, at a minimum, to evaluate industry innovations in this domain. This would include broadening the knowledge of pathogen characteristics and spread, as well as experiences from owners, operators and users dealing with this matter.
2. Criteria and methodology for assessment of specific ventilation requirements for transit facilities and vehicles should be established, especially requirements for fresh air exchange rates for enclosed transit rooms while considering density of transit riders and employees, specific features of transit facilities and vehicles, and related HVAC systems.
3. Technical and performance specifications for ventilation or air purification/sanitization measures should be developed for application in tenders for new rolling stock, refurbishment of existing rolling stock, new station design, and refurbishing existing and/or grandfathered stations.
4. Standardizing testing and related quality assurance methodology, specifically for transit, should be established in relation to recommended ventilation and air sanitization measures, as well as for individual architectural interventions dealing with sanitizing high-touch surfaces.
5. New station design guidelines should be established in terms of selection of individual measures or combination thereof that exhibit highest efficiencies in terms of rider and employee safety.
6. Station design or refurbishment should promote the concept of “light and air” as well as one-way flows and equal distribution of passengers throughout a transit facility and/or vehicle. One could also consider a pandemic scenario that temporarily switches certain key stations to entry- or exit-only stations to promote unidirectional passenger flow. The use of pedestrian simulation software to test and refine station design should be the norm.
7. 3D airflow simulations should be established for buses and other rolling stock in order to improve cabin air circulation and avoid local air-recirculation zones where pathogens might stall, for both summer and winter conditions.
8. Air purification and sanitization with agents such as hydrogen peroxide, ozone or ions are broadly used in other industries (agriculture, food, healthcare, etc.). Historical experiences, lessons learned and new research on the subject should be shared and published to improve the understanding and to facilitate the use of these technologies for transit purposes. Such a holistic and integrated approach would facilitate innovations and utilization of these technologies for public transit as well as allow adequate assessment of their safety, required dosage, and design, including appropriate 3D simulations, maintenance, operations, reliability and efficiency.
9. A simple mathematical model should be developed to quantitatively describe the risk of COVID-19 indoor airborne infection transmission based on the carbon dioxide concentration [5].

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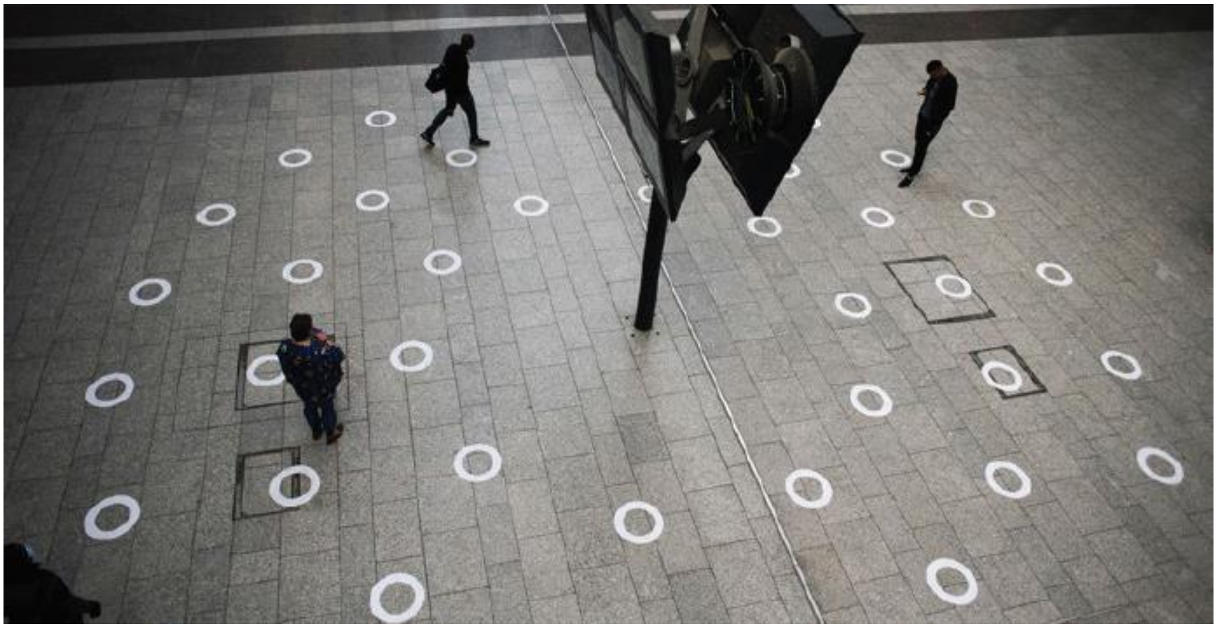
Abbreviations and acronyms

µm	micrometer
ACE2	angiotensin-converting enzyme 2
ACGIH	American Conference of Governmental Industrial Hygienists
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BART	Bay Area Rapid Transit
CDC	Centers for Disease Control and Prevention
CFD	computational fluid dynamics
cfm	cubic feet per minute
CIH	Certified Industrial Hygienist
CO_2	carbon dioxide
EPA	Environmental Protection Agency
H_2O_2	hydrogen peroxide
HEPA	high-efficiency particulate air
HVAC	heating, ventilation and air conditioning
LED	light-emitting diode
lpm	liters per minute
MARC	Maryland Area Regional Commuter
MERV	Minimum Efficiency Reporting Value
MTR	Mass Transit Railway (Hong Kong)
NIOSH	National Institute of Occupational Safety and Health
O&M	Operations and Maintenance
OMNY	One Metro New York
OSHA	Occupational Safety and Health Administration
PCO	photocatalytic oxidation
PEL	permissible exposure limit
PHI	photohydroionization
PPE	personal protective equipment
ppm	parts per million
PSD	platform screen door
REL	recommended exposure limit
RKI	Robert Koch Institute
SARS	severe acute respiratory syndrome
SAS	Surface Air System
TLV	threshold limit value
TRB	Transportation Research Board
TVM	ticket vending machine
TWA	time-weighted average
UV	ultraviolet
WHO	World Health Organization

Appendix A: Examples of industry-implemented measures



Signage on floors showing distancing requirement at Gare du Nord train station, Paris.

General signage at NYCT subway stations, New York.

Reconfiguring seating to promote physical distancing at Andhra Pradesh State Road Transport Corporation, India.

Barriers and signage guiding pedestrian traffic at Amazon warehouse to provide physical distancing.

Touch-free automatic fare gate at MBTA Kenmore T Station and Haymarket Station, Boston. Features contactless automated entry through tap-on payment and wider gate aisles with increased accessibility.
http://www.ecs.umass.edu/umass_itps_workshop/slides_brooks.pdf

Antimicrobial powder coating at Mass Transit Railway, Hong Kong. High-touch surfaces in antimicrobial powder coat finish. https://www.insider.com/hong-kong-mtr-better-than-the-london-underground-new-york-subway-2018-1#the-first-thing-you-notice-just-how-clean-everything-is-1

Appendix B: Additional architectural renderings

Fare gate area with overhead air purification system

Fare gate area with vertical air purification system

Platform area with architectural and ventilation interventions

Ticketing area with architectural and ventilation interventions

Paid area with architectural and ventilation interventions

Close-up view of touch-free fare gate

Appendix C: Standardized testing methodology and procedures

The following represents a potential methodology for transit car testing where an air purification system using hydrogen peroxide has been implemented (source: https://unitedsafetycorporation.com/).

Sampling

Sampling is performed on one bus or one train car with an air purification system installed and on one bus or one train car without an air purification system. Samples will be collected on each vehicle, bus or train car, during an initial episode of air purification introduction and then again approximately four hours later during a "steady state" episode when the air purification system works continuously in concert with the HVAC system.

Air samples will be collected utilizing an SAS 100 Air Sampler. Three air samples will be collected at the front, middle and rear of each bus/car during the four sampling episodes for a total of 12 air samples collected. Surface samples will be collected from potential high-contact surfaces using sterile swabs. The swabs will also be collected from surfaces at the front, middle and rear of each bus during the four sampling episodes for a total of 12 surface samples collected. Air and surface samples will be analyzed for identification and enumeration of culturable bacteria (pathogens) at a certified laboratory using M011 analysis (identification and enumeration of culturable bacteria, up to five types).

Sampling personnel will have personal protective equipment while conducting the bacteria sampling episodes, including (at a minimum) disposable suits, boots, gloves and N-95 respirators. Testing will be conducted by a Certified Industrial Hygienist (CIH) providing technical guidance, assessment protocols, report preparation and quality control during the project. The final report will consist of the sample information and results.

Transit owner/operator facility responsibilities

- Industrial hygienist is present during all sampling activities.
- Notification is provided to transit employees (bus/railcar operators) and to facility occupants of the pending sampling activities.
- Safe access is provided to testing staff to all areas where the sampling will occur.

Schedule and reporting

- Testing is to be scheduled at a mutually agreed-upon time and location.
- For best results and to the extent possible, "in-service" testing should be conducted using comparable railcars/buses on the same service routing with similar passenger loading and run times. Any variations in passenger loading or operations will be noted in the reporting.
- Testing procedures and protocols should be harmonized among agencies, operators and owners, and shall be generally accepted by relevant stakeholders (maintenance staff, staff in trains, buses or offices, etc.).

Testing for air sanitizing using hydrogen peroxide (H_2O_2)

- Sampling and analytical method shall follow OSHA Method 1019.
- Exposure limits shall follow:
  - OSHA permissible exposure limit (PEL), 8-hour time-weighted average (TWA): 1 ppm (1.4 mg/m^3)
  - NIOSH recommended exposure limit (REL), up to 10-hour TWA: 1 ppm (1.4 mg/m^3)

- American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV), 8-hour TWA: 1 ppm
- California/OSHA PEL, 8-hour TWA: 1 ppm (1.4 mg/m^3)

- Sampling methodology:
  - Media: two-piece cassette with two 25 mm quartz fiber filters coated with titanium oxysulfate
  - Air volume: 240 liters
  - Flow rate: 1 lpm
- Sample analysis:
  - Samples are extracted with 10 mL of 1 M H2SO4 and analyzed by spectrophotometry
  - Reliable quantitation limit: 36.6 ppm/50.8 µg/m^3
- Sampling procedure for transit cars with photohydroionization:
  - Ensure that PHI cell is operating for the duration of the sampling event.
  - Collect TWA samples in operator area:
    - Collect samples representative of height of average breathing zone at seated position (approximately 52 in.).
    - Collect samples representative of height of average breathing zone at standing position (approximately 71 in.).
  - Collect TWA samples in passenger areas directly below PHI cells:
    - Collect samples representative of height of average breathing zone at seated position (approximately 52 in.).
    - Collect samples representative of height of average breathing zone at standing position (approximately 71 in.).
  - Collect TWA samples in passenger area at midcar location between PHI cells:
    - Collect samples representative of height of average breathing zone at seated position (approximately 52 in.).
    - Collect samples representative of height of average breathing zone at standing position (approximately 71 in.).
  - Collect TWA sample in reference location:
    - Collect sample in car without PHI cell at a position or positions similar to the locations listed above.
    - Collect samples outside of car to determine if any ambient source or concentration of hydrogen peroxide is present that may impact sampling episode inside the transit cars.
  - Submit at least one blank per sampling episode/set of samples.
- Analytical results interpretation:
  - Compare analytical results to OSHA PEL to determine if a potential exposure hazard to passengers and operators exists.
    - If sample concentrations are over or at PEL, evaluate potential engineering, ventilation or administrative controls to reduce exposure.
    - If sample concentrations are within 50 percent of PEL, determine if other potential sources are present and are impacting ambient concentrations within the transit cars.
    - If sample concentrations are less than 50 percent of PEL, consider a routine monitoring plan to ensure that concentrations do not exceed any enforceable or published exposure limits.
    - If exposure limits change, consider additional monitoring to determine if new limits are approached or exceeded.

Appendix D: Evaluation matrices

ARCHITECTURAL AND VENTILATION / HVAC INTERVENTIONS TO PROMOTE SAFE MOBILITY IN POST COVID-19 TRANSIT FACILITIES

UNDERGROUND (ENCLOSED) STATIONS (PATRONS, OPERATION & MAINTENANCE STAFF)

Intervention type	Category	Measure	EFFECTIVENESS	EASE OF APPLICATION	CAPITAL INVESTMENT (COST)	O & M COSTS LOWERED	EQUITY ACHIEVED	OVERALL RATING
ARCHITECTURAL INTERVENTIONS	01 PHYSICAL DISTANCING	Guiding Pedestrian Traffic (Barriers & Signage)	High	High	$$	✓	⚖	H
		Showing X' Distancing Requirement & Managing Boarding (Signage on Platform)	High	High	$		⚖	H
		Displaying Real-Time Passenger Density in Train Cars (Phone Apps)	High	Moderate	$$			M
		Displaying Real-Time Passenger Density & Other Various Info (Electronic Screens)	High	Low	$$$		⚖	M
		Reconfiguring Seating (Promoting Physical Distancing)	High	Moderate	$$		⚖	H
		Patron Counting (Monitoring Density at Entry Points)	Moderate	Low	$$		⚖	L
	02 TOUCH-FREE DEVICES	Automatic Fare Collection (Touch-Free System at Fare-Gates)	High	Moderate	$$		⚖	H
		Phone App-based Fare Collection	High	Moderate	$$			M
		Voice Activated Systems (Ticketing Vending Machines, Elevators)	Moderate	Moderate	$$$			M
		Automatic Door Opening Systems	High	Moderate	$$		⚖	H
		Touch-free Devices & Accessories (Soap & Paper-Towel Dispensers, Trash Receptacles, etc.)	High	High	$	✓	⚖	H
	03 SURFACE TREATMENTS	Extended Life Antimicrobial Surface Treatment (for High-Frequency Handled Surfaces)	High	Moderate	$$	✓	⚖	H
		Copper Coating / Patch (for High-Frequency Handled Surfaces)	Moderate	Low	$$$	✓	⚖	L
		Self-Cleaning Nano Coating (for High-Frequency Handled Surfaces)	High	High	$$	✓	⚖	H
		Self-Cleaning Devices Utilizing UV-C Lights for Escalator Handrails	High	High	$$	✓	⚖	H
		Display Cleaning Logs (in Public Areas and Restrooms)	High	High	$	✓	⚖	H
VENTILATION INTERVENTIONS	04 VENTILATION AND AIR SANITIZATION	Adding Filters (Electro-Static, Mechanical) to Ventilation System	Moderate	Moderate	$$	✓	⚖	M
		Increasing Air Exchange Rate in Public and Service Areas	High	Moderate	$$	✓	⚖	H
		Air Sanitization Portals at Turnstiles	High	Moderate	$$	✓	⚖	H
		Air Sanitization at Staff Service Rooms	High	Moderate	$$	✓	⚖	H
		Patron-Density Dependent Air Flow Interventions (Considering Peak-Time Ridership)	High	High	$$	✓	⚖	H
		Integration of Air Purification & HVAC System for Improved Air Quality	High	Moderate	$$$	✓	⚖	H

GRAPHIC LEGEND

Symbol	Meaning
⚖	Equity* Achieved
	*Equity: Treating all patrons in a fair & unbiased way and providing universally accessible measures
●	High
◐	Moderate
○	Low
$	Cost- Low
$$	Cost- Moderate
$$$	Cost- High
✓	Measure results in lowering long-term operation and maintenance costs
H	Overall rating- High
M	Overall rating- Moderate
L	Overall rating- Low

ARCHITECTURAL AND VENTILATION / HVAC INTERVENTIONS TO PROMOTE SAFE MOBILITY IN POST COVID-19 TRANSIT FACILITIES

AT-GRADE (OPEN) STATIONS (PATRONS, OPERATION & MAINTENANCE STAFF)

Intervention type	Category	Measure	Effectiveness	Ease of Application	Capital Investment (Cost)	O & M Costs Lowered	Equity Achieved	Overall Rating
Architectural Interventions	01 Physical Distancing	Guiding Pedestrian Traffic (Barriers & Signage)	●	●	$$	✓	⚖	H
		Showing X' Distancing Requirement & Managing Boarding (Signage on Platform)	●	●	$		⚖	H
		Displaying Real-Time Passenger Density in Transit Rail Vehicles/Buses (Phone Apps)	●	◑	$$			M
		Displaying Real-Time Passenger Density & Other Various Info (Electronic Screens)	●	○	$$$		⚖	M
		Reconfiguring Seating (Promoting Physical Distancing)	●	◑	$$		⚖	H
		Patron Counting (Monitoring Density at Entry Points)	◑	○	$$		⚖	L
	02 Touch-Free Devices	Automatic Fare Collection (Touch-Free System at Fare-Gates)	●	◑	$$		⚖	H
		Phone App-based Fare Collection	●	◑	$$			M
		Voice Activated Systems (Ticketing Vending Machines, Elevators)	◑	◑	$$$			M
		Automatic Door Opening Systems	●	◑	$$		⚖	H
		Touch-free Devices & Accessories (Soap & Paper-Towel Dispensers, Trash Receptacles, etc.)	●	●	$	✓	⚖	H
	03 Surface Treatments	Extended Life Antimicrobial Surface Treatment (for High-Frequency Handled Surfaces)	●	◑	$$	✓	⚖	H
		Copper Coating / Patch (for High-Frequency Handled Surfaces)	◑	○	$$$	✓	⚖	L
		Self-Cleaning Nano Coating (for High-Frequency Handled Surfaces)	●	●	$$	✓	⚖	H
		Self-Cleaning Devices Utilizing UV-C Lights for Escalator Handrails	●	●	$$	✓	⚖	H
		Display Cleaning Logs (in Public Areas and Restrooms)	●	●	$	✓	⚖	H
Ventilation Interventions	04 Ventilation and Air Sanitization	Air Sanitization Portals at Turnstiles	●	◑	$$	✓	⚖	H
		Air Sanitization at Staff Service Rooms	●	◑	$$	✓	⚖	H
		Increasing Air Exchange Rate in Service Area	●	◑	$$	✓	⚖	H

GRAPHIC LEGEND

- ⚖ Equity* Achieved
- *Equity: Treating all patrons in a fair & unbiased way and providing universally accessible measures
- ● High
- ◑ Moderate
- ○ Low
- $ Cost- Low
- $$ Cost- Moderate
- $$$ Cost- High
- ✓ Measure results in lowering long-term operation and maintenance costs
- H Overall rating- High
- M Overall rating- Moderate
- L Overall rating- Low

ARCHITECTURAL AND VENTILATION / HVAC INTERVENTIONS TO PROMOTE SAFE MOBILITY IN POST COVID-19 TRANSIT FACILITIES

TRANSIT RAIL VEHICLES

Intervention type	Category	Measure	Effectiveness	Ease of Application	Capital Investment (Cost)	O & M Costs Lowered	Equity Achieved	Overall Rating
Architectural Interventions	01 Physical Distancing	Showing X' Distancing Requirement (Signage in Rail Vehicles)	High	High	$		Equity achieved	H
Architectural Interventions	01 Physical Distancing	Measuring Real-Time Passenger Density in Rail Vehicles (Phone Apps)	Moderate	Moderate	$$			M
Architectural Interventions	01 Physical Distancing	Measuring Real-Time Passenger Density & Other Various Info (Electronic Indicators)	Moderate	Low	$$$		Equity achieved	M
Architectural Interventions	01 Physical Distancing	Reconfiguring Seating (Promoting Physical Distancing)	High	Moderate	$$		Equity achieved	H
Architectural Interventions	02 Touch-Free Devices	Onboard Toilet Facilities w/ Touch-Free Devices	High	Moderate	$$	✓	Equity achieved	H
Architectural Interventions	02 Touch-Free Devices	Touch-Free Onboard Ticketing	High	Moderate	$$			M
Architectural Interventions	03 Surface Treatments	Extended Life Antimicrobial Surface Treatment (for High-Frequency Handled Surfaces)	High	Moderate	$$	✓	Equity achieved	H
Architectural Interventions	03 Surface Treatments	Copper Coating / Patch (for High-Frequency Handled Surfaces)	Moderate	Low	$$$	✓	Equity achieved	L
Architectural Interventions	03 Surface Treatments	Self-Cleaning Nano Coating (for High-Frequency Handled Surfaces)	High	High	$$	✓	Equity achieved	H
Architectural Interventions	03 Surface Treatments	Display Cleaning Logs	High	High	$	✓	Equity achieved	H
Ventilation Interventions	04 Ventilation and Air Sanitization	Adding Filters (Electro-Static, Mechanical) to Ventilation System	Moderate	Moderate	$$	✓	Equity achieved	M
Ventilation Interventions	04 Ventilation and Air Sanitization	Increasing Air Exchange Rate	High	Moderate	$$	✓	Equity achieved	H
Ventilation Interventions	04 Ventilation and Air Sanitization	Air Sanitization in Transit Rail Vehicles	High	Moderate	$$	✓	Equity achieved	H
Ventilation Interventions	04 Ventilation and Air Sanitization	Individually Protected Air Treatment for Operator/Engineer	High	Moderate	$$	✓	Equity achieved	H

GRAPHIC LEGEND

- Equity* Achieved — *Equity: Treating all patrons in a fair & unbiased way and providing universally accessible measures
- ● High; ◐ Moderate; ○ Low
- $ Cost- Low; $$ Cost- Moderate; $$$ Cost- High
- ✓ Measure results in lowering long-term operation and maintenance costs
- H Overall rating- High; M Overall rating- Moderate; L Overall rating- Low

ARCHITECTURAL AND VENTILATION / HVAC INTERVENTIONS TO PROMOTE SAFE MOBILITY IN POST COVID-19 TRANSIT FACILITIES

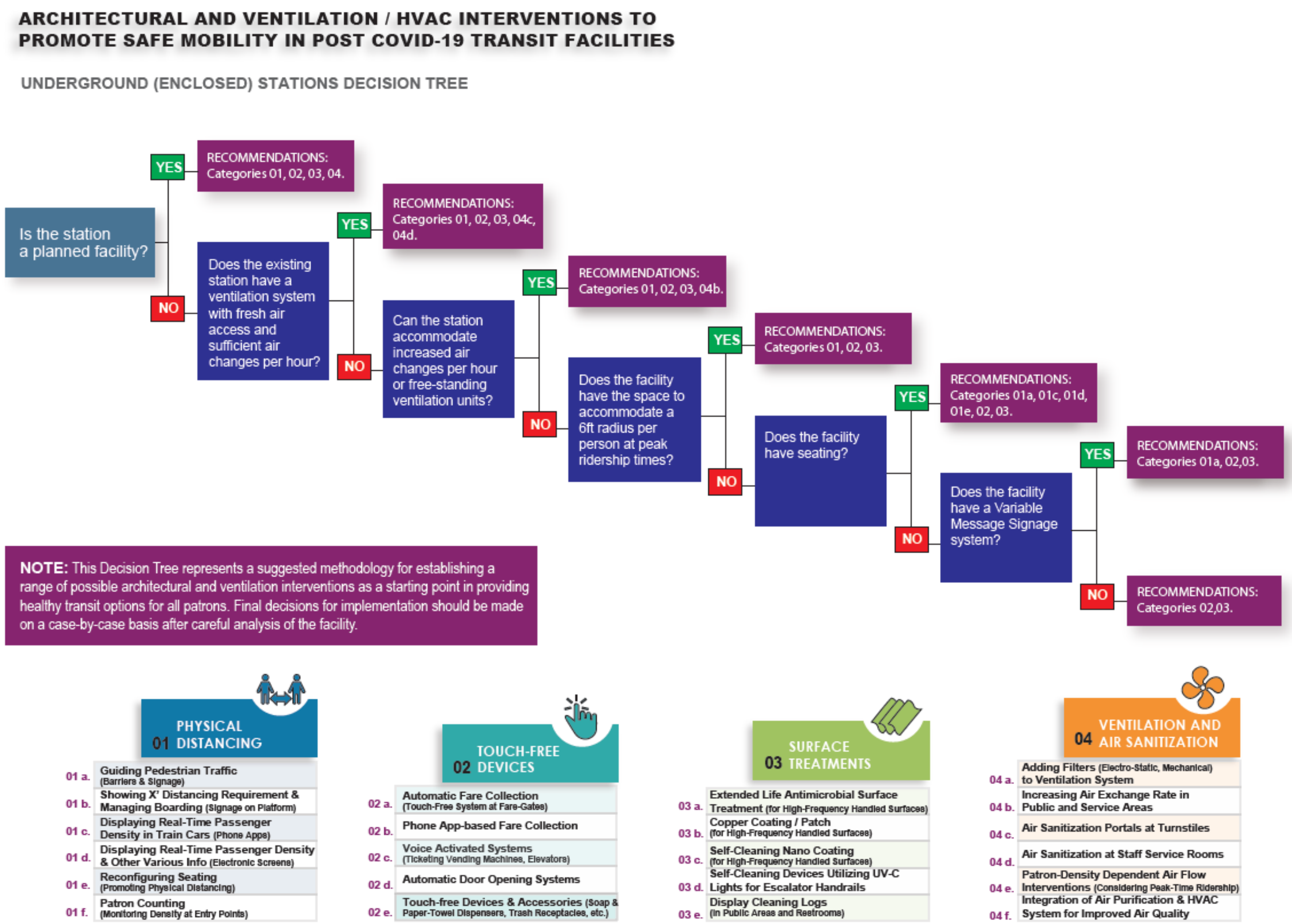
BUSES

Intervention type	Category	Measure	Effectiveness	Ease of Application	Capital Investment (Cost)	O & M Costs Lowered	Equity Achieved	Overall Rating
Architectural Interventions	01 Physical Distancing	Showing X' Distancing Requirement (Signage in Rail Vehicles)	High	High	$		Achieved	H
		Measuring Real-Time Passenger Density in Buses (Phone Apps)	Moderate	Moderate	$$			M
		Measuring Real-Time Passenger Density & Other Various Info (Electronic Indicators)	Moderate	Low	$$$		Achieved	M
		Reconfiguring Seating (Promoting Physical Distancing)	High	Moderate	$$		Achieved	H
		Driver Protection Shield	High	High	$		Achieved	H
		Dual Purpose Lockout Seating	High	Moderate	$$		Achieved	H
	02 Touch-Free Devices	Onboard Stop Indicators	High	Moderate	$$		Achieved	H
		Cashless/Offboard Fare Collection Systems	High	Moderate	$$		Achieved	H
		Auto Adjust Seating	High	Moderate	$$		Achieved	H
		No Touch Operator Switches (Proximity Activation, Foot Control)	High	Moderate	$$		Achieved	H
		Antimicrobial Inductive Phone Charger Trays	High	Moderate	$$$			H
		Automated ADA Securement	High	Moderate	$$		Achieved	H
	03 Surface Treatments	Extended Life Antimicrobial Surface Treatment (for High-Frequency Handled Surfaces)	High	Moderate	$$	✓	Achieved	H
		Copper Coating / Patch (for High-Frequency Handled Surfaces)	Moderate	Low	$$$	✓	Achieved	L
		Self-Cleaning Nano Coating (for High-Frequency Handled Surfaces)	High	High	$$	✓	Achieved	H
		Display Cleaning Logs	High	High	$	✓	Achieved	H
		Antimicrobial Injection Molded Plastics	High	High	$$	✓	Achieved	H
Ventilation Interventions	04 Ventilation and Air Sanitization	Adding Filters (Electro-Static, Mechanical) to Ventilation System	Moderate	Moderate	$$	✓	Achieved	M
		Increasing Air Exchange Rate	High	Moderate	$$	✓	Achieved	H
		Air Sanitization in Buses	High	Moderate	$$	✓	Achieved	H
		Dynamic Antimicrobial Air Treatment	High	Moderate	$$	✓	Achieved	H
		Individually Protected Air Treatment for Operator/Engineer	High	Moderate	$$	✓	Achieved	H

GRAPHIC LEGEND

- Equity* Achieved
- *Equity: Treating all patrons in a fair & unbiased way and providing universally accessible measures
- ● High
- ◐ Moderate
- ○ Low
- $ Cost- Low
- $$ Cost- Moderate
- $$$ Cost- High
- ✓ Measure results in lowering long-term operation and maintenance costs
- H Overall rating- High
- M Overall rating- Moderate
- L Overall rating- Low

Appendix E: Decision trees



ARCHITECTURAL AND VENTILATION / HVAC INTERVENTIONS TO PROMOTE SAFE MOBILITY IN POST COVID-19 TRANSIT FACILITIES

TRANSIT RAIL VEHICLES AND BUSES DECISION TREE