The National Preparedness Leadership Initiative is a joint program of the Harvard T.H. Chan School of Public Health and the Harvard Kennedy School of Government, Center for Public Leadership

Aviation Public Health Initiative

Assessment of Risks of SARS-CoV-2 Transmission During Air Travel and Non-Pharmaceutical Interventions to Reduce Risk

Phase Two Report: Curb-to-Curb Travel Through Airports

Prepared by

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ACKNOWLEDGEMENTS

This project arose in response to a complex set of problems during an unprecedented crisis. Three months into the COVID-19 pandemic, the aviation industry faced a significant decline in passenger traffic and revenue. There was interest in finding an independent, science-based resource to answer difficult public health safety questions, critical to both protect the workforce and the public, and essential to restarting this important segment of the national economy. Out of that interest to reopen the sector safely, discussions began between Airlines for America (A4A) and faculty at the National Preparedness Leadership Initiative (NPLI), a joint program of the Harvard T.H. Chan School of Public Health and the Harvard Kennedy School of Government. Those conversations led to development of the Aviation Public Health Initiative (APHI).

As lead sponsoring organization, A4A engaged their member organizations along with a group of manufacturers and airport operators. These companies generously provided financial support, shared data and information, facilitated conversations with airport COVID-19 working groups, and opened opportunities to speak with the airport operators. That breadth of conversation and data access was critical to collecting the body of knowledge required to reach the findings and recommendations in this report. That interest led to discussions and briefs with numerous government officials associated with the aviation industry. Through it all, this group of industry and government leaders respected the independence of the APHI scientists and their research.

The APHI project team includes faculty and associates of the Harvard T.H. Chan School of Public Health. The remarkable cadre of people who came together – most of whom worked exclusively in a virtual environment – devoted countless hours in pursuit of answers to deeply complex questions. The leadership includes Director Leonard J. Marcus, PhD; Deputy Director Vice Admiral Peter V. Neffenger, USCG (ret); Science Director John D. Spengler, PhD; Deputy Science Director John F. McCarthy, ScD, C.I.H.; Infectious Disease Consultant, Edward A. Nardell, MD, and Lead Science and Technical Writer Wendy M. Purcell, PhD, FRSA. The project team includes Senior Project Manager Leila Roumani, DMD, MPH and Communications Specialist Richard Ades. The science and technology research team includes Ramon Alberto Sanchez, ScD; Ted Myatt, ScD; Jose Guillermo Cedeno Laurent, PhD; Jerry F. Ludwig, PhD; Steve Hanna, PhD; Judith Irene Rodriquez, MS, and David MacIntosh, ScD, C.I.H., DABT. Susan Flaherty, Regina Jungbluth, Michelle Tracanna, and Joan Arnold provided essential administrative support and Brigid Loureiro ably managed production of the final document. The team acknowledge the technical contributions of Jelena Srebric, PhD and Shengwei Zhu, PhD from The Center for Sustainability in the Built Environment at the University of Maryland. Brad Prezant, MBA, MSPH of VA Science provided assistance with modeling of airports. This Phase Two report benefited greatly from the generous contributions of Michael Mina, MD (Harvard T.H. Chan School of Public Health) and Donald Milton, MD (University of Maryland).

The findings and recommendations of this report are the independent conclusions of the Harvard T.H. Chan School of Public Health Aviation Public Health Initiative (APHI). The APHI team hopes the contents of this report will underscore the importance of following the science of SARS-CoV-2 in order to save lives, reinvigorate our economy, and help lead the country and the world in efforts to overcome the COVID-19 crisis.

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LIST OF ABBREVIATIONS AND ACRONYMS

A4A	Airlines for America
ACE2	Angiotensin Converting Enzyme 2
ACH	Air Changes per Hour
AIHA	American Industrial Hygiene Association
APHI	Aviation Public Health Initiative
APU	Auxiliary Power Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
ATP	Adenosine Triphosphate
CAAT	Civil Aviation Authority of Thailand
CAR	Central African Republic
CDC	Centers for Disease Control and Prevention
CFD	Computational Fluid Dynamics
cfm	cubic feet per minute
cm/s	centimeters per second
CO_2	carbon dioxide
DNA	Deoxyribonucleic Acid
EASA	European Union Aviation Safety Agency
ECS	Environmental Control System
GUV	Germicidal Ultraviolet
HEPA	High Efficiency Particulate Air
IATA	International Air Transport Association
l/s/p	liter per second per person
MERS-CoV	Middle Eastern respiratory syndrome coronavirus
MERV	minimum efficiency reporting value
NAS	National Academies of Sciences
nm	nanometer
NPI	Non-Pharmaceutical Intervention
PCA	Pre-conditioned Air
PPE	Personal Protective Equipment
ppm	parts per million
ppmv	parts per million per volume
PRNT	Plaque Reduction Neutralization Test
PUIs	Persons Under Investigation
QAC	Quaternary Ammonium Compound
RH	Relative Humidity
RNA	Ribonucleic Acid
RT-PCR	Reverse Transcription Polymerase Chain Reaction
S&T	Science and Technical
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SEIR	Susceptible – Exposed – Infected – Recovered
WGS	Whole-genome Sequencing
WHO	World Health Organization
µm	micrometer

1.0 EXECUTIVE SUMMARY

The Harvard T.H. Chan School of Public Health, Aviation Public Health Initiative (APHI), prepared this Phase Two 'Curb-to-Curb' report. Its focus is the examination and risk mitigation of SARS-CoV-2 transmission at airports. It is the second report developed by the APHI, the first being the Phase One 'Gate-to-Gate' report that focused on reducing the risks of SARS-CoV-2 on aircraft (Harvard APHI, 2020).

The report is an independent scientifically based analysis of the COVID-19 crisis as it applies to travel through airports. The primary research reported here reflects data secured through a survey of 25 airports, 23 within the United States (U.S.) and two elsewhere, interviews with six U.S. airports, specialized modelling studies and visits to two U.S. airports. The team also interviewed representatives of the U.S. Transportation Security Administration (TSA), U.S. Customs and Border Protection (CBP), associations representing the airport industry, and specialists in virus testing, ventilation systems, and indoor chemistry related to cleaning and disinfection. An ongoing dialogue with a consortium of airport and airline operators, aviation industry manufacturers, and aviation sector bodies also helped inform the multidisciplinary scientific and technical APHI team.

The sample of U.S. airports reflected different areas of the country, airport sizes, and international and domestic facilities. While there are common features among the approximately 450 commercial airports in the U.S., such as federal security processes, they vary in terms of their governance, culture, infrastructure, and volume of passengers. Despite this variety, the surveys and interviews together with the modelling studies provide a substantive basis upon which to assess airport pandemic practices and to offer recommendations relevant to reducing the risks of SARS-CoV-2 transmission in airport settings.

The report presents the scientific evidence in support of adopting a non-pharmaceutical intervention (NPI) strategy, using a layered approach, to control the transmission of the novel coronavirus SARS-CoV-2 in the airport environment. The APHI team recognize that airports are layering risk mitigation strategies to reduce SARS-CoV-2 transmission for passengers, employees, concessionaires, contractors, and visitors. Current practices target activities that address known routes of SARS-CoV-2 transmission. Further tailored application of the layered NPI approach can mitigate risk in airport settings and help restore public confidence in air travel, considered essential to a global economic recovery. The report offers a series of recommendations for risk mitigation against SARS-CoV-2 in airports.

1.1 CONTEXT

This report focuses on the traveler's journey, whether departing, arriving or connecting (including any inter-airport transfers, i.e., terminal to terminal), designated as 'Curb-to-Curb' travel. The report considers passenger activities from the point at which they arrive at the airport terminal, curbside or entrance, and includes check-in, baggage drop-off, security screening, concessions, support facilities (such as dining, shopping, and restrooms), and departure hold rooms at the gate area before entering the jetway to board the aircraft. After the flight, the Curb-to-Curb traveler journey continues from the point the passenger disembarks the jetway and enters the terminal building, international passengers will pass through immigration and customs (in the U.S., CBP) facilities, baggage claim, to when they leave the terminal. When airside, the use of buses, trams, trains, etc. are included as part of the traveler journey; however, travel to and from the airport is excluded. The focus of this report is on passengers using airport facilities across a 'typical' trip in the manner common to economy class customers. Passengers with special status who might enjoy shorter processing time through security or customs or avoid crowded gate areas by using lounges and/or boarding first were not considered separately. Employees of airports, airlines, security and customs staff, concessionaires and others who work on airport property typically spend longer inside an airport and use other spaces compared to a typical passenger. Many also interact with passengers on a regular basis. As such, where appropriate, any relevant differences in risk among employee settings are highlighted.

While the NPI framework for assessing and mitigating risk of SARS-CoV-2 transmission is similar for both the airport and the aircraft phases, the airport environment is much more complex than an aircraft in considering SARS-CoV-2 transmission risks and mitigation efforts. For example, once onboard the aircraft, passenger movements are restricted and can be monitored, people are seated and mostly facing the same direction and the ventilation system is designed to filter, dilute, and rapidly remove contaminants from the breathing zone. In an airport terminal, passengers undertake a range of activities, some of which are defined (e.g., checking-in, dropping off baggage, going through the security check, and queuing in the gate area). Other activities are discretionary, such as spending time in one of the concessionaires, dining at a restaurant or bar (depending on restrictions that may be in place from state and local authorities), using the restrooms, or relaxing in one of the lounge areas. Travelers spend time in different physical spaces within the airport for varying amounts of time. As such, relative to being onboard an aircraft, passenger movements are comparatively unrestricted in an airport terminal. Diverse airport terminal layouts affect ventilation rates and congestion, with airline schedules and daily/seasonal travel cycles influencing passenger numbers and congregation patterns.

The design of the recommended NPI measures conform to a generic airport operational context, recognizing that no two airports are alike. The layered approach to risk mitigation lends itself to the design of a combination of engineering and physical controls as well as

hygiene and physical distancing measures that can be tailored to a particular airport terminal setting.

Every year, millions of passengers efficiently and safely make their way through airports. In response to the COVID-19 pandemic, airport operators and key stakeholders acted promptly to reduce the risks of disease transmission in their facilities. Without extensive contact tracing and testing, it is difficult to measure the success of these measures. While the International Civil Aviation Organization (ICAO) as of December 2020 reported that of scheduled flights carrying over 2.8 billion passengers internationally, there have been no recorded outbreaks among passengers at airports, assessing overall transmission rates in airport environments is notoriously difficult. While airport operators followed guidance from the Centers for Disease Control and Prevention (CDC) and state and local health authorities, they were largely responsible for determining their own strategy, with a variety of practices seen in the U.S. and internationally. Further complicating the situation, different airlines operating in the same airport adopted slightly different policies and protocols, adding to passenger confusion about COVID-19 prevention protocols.

Mitigating the risk of transmission of SARS-CoV-2 is a shared responsibility between passengers and airport operators in concert with others including airlines, concessionaires, security, immigration and customs and others who work in or visit terminals. Passengers seeking to reduce the risk of contracting SARS-CoV-2 need to comply strictly with wearing a face mask, observing physical distancing, and practicing personal hygiene protocols. The presidential executive order issued on January 21, 2021 mandates that "masks to be worn in compliance with CDC guidelines in or on: airports, commercial aircraft…" and a number of other public conveyance locales (The White House, 2021). While the challenges of behavioral compliance are particularly complex in the airport environment, airports have found success in affording passengers easy opportunities to make risk-mitigating choices. Going forward, maintaining the public health agenda remains an imperative for airport operators.

Given recent reports of more contagious SARS-CoV-2 variants (see Chapter 2), comprehensive compliance with face mask/covering requirements will likely remain a first-order action to mitigate transmission, even as more and more people are vaccinated. In addition to the measures already underway by airports (Chapter 3), cleaning and disinfection (Chapter 4), viral testing (Chapter 5), health screening (Chapter 6) and ventilation (Chapter 7) can be used to enhance risk mitigation. The CDC now recommends enhanced ventilation (in some settings) as an important component of a layered approach to mitigate the risk of transmission of SARS-CoV-2. At the same time, airports are cautioned to avoid implementing any unproven measures that are of limited or no material effect, or that might even increase the risk of transmission (see Chapters 4 and 7).

The scientific basis and rationale of the recommendations in this Curb-to-Curb report are presented in detail in Chapters 3 through 7, alongside relevant reference to other studies and data so that key findings may be placed in context. What follows here are the key findings and highlights from the report, arranged by chapter. Readers are encouraged to review in detail the relevant chapter to gain a full understanding of the key findings.

1.2 KEY FINDINGS AND REPORT HIGHLIGHTS

1.2.1 Chapter 3: Airport Practices

- Airports in the study were determined to be making concerted efforts to reduce the risk of SARS-CoV-2 transmission in the airport environment as it relates to the Curb-to-Curb traveler experience by layering risk mitigation strategies.

- The mitigation strategies used by airports in the study demonstrated a substantive grasp of SARS-CoV-2 transmission routes, with timely interventions designed to reduce spread by all known routes relevant to the health and safety of passengers and employees as well as concessionaires, contractors, and visitors.

- Current practices by the airports surveyed included enhanced cleaning and disinfection regimens, upgrades to ventilation delivery and air handling systems (including increasing filtration efficiency), adoption of various means to encourage physical distancing (e.g., floor decals, barriers, signage, communication), promoting compliance with wearing face coverings/masks and use of technology to support contactless procedures in certain circumstances. Collectively, these efforts play an important role in providing layers of protection and risk mitigation to reduce transmission of SARS-CoV-2 in airport settings and can help restore traveler confidence.

- Innovation in the sector is strong, as seen in the adoption of contactless technologies, sensors, and automation of process and procedures. Use of these technologies also usually mean faster processing, which could further reduce congestion and risk.

- There was a variety of practices across airport employees, tenants, contractors, and visitors. Further consistency will support peer-to-peer compliance as well as make it easier for passengers to understand what is expected of them. Aviation industry-wide consistency, which could be achieved through federal requirements in the U.S., would promote faster dissemination of good practices, help support passenger confidence and enable targeted financial investments in support of faster industry-wide recovery.

- In some states, airport restaurants were required to close seated dining (even if properly spaced) in line with state or local rules, with food pick-up and delivery only. The unintended consequence of this policy resulted in increased congestion in gated and seated areas and mixing of unmasked (face mask removed to eat or drink) with masked travelers. This is an example where one precautionary measure could potentially exacerbate overall transmission risks. Concerned airports lobbied states to change these policies, and the science supports the importance of these considerations in overall risk mitigation.

- Airports expressed concern about the ability to maintain physical distancing once passenger volume increases. For example, with current reduced flows, the number of active airport gates can be distanced to avoid concourse crowding. The layered approach to risk mitigation is relevant here as it affords a level of 'redundancy' so that when some practices are not possible (e.g., maintaining physical distancing of 6-feet/1.83 meters), the proper wearing of face masks and enhanced operation of ventilation systems might still usefully mitigate risks of transmission, for example.

- Overall, the airports in the study are implementing comprehensive strategies to mitigate the impact of COVID-19 on their employees, passengers, and the wider airport community. They have adopted a layered risk mitigation approach in line with the science of SARS-CoV-2 and known routes of transmission. Good practices are present across the airport operator surveyed. Greater harmonization of practices across the industry will support focused investment and preclude investments that offer little risk mitigation benefit.

1.2.2 Chapter 4: NPI Risk Mitigation

- Face coverings/masks are highly effective in preventing SARS-CoV-2 infections caused by large virus-containing droplets and aerosols. All passengers should wear a face covering/mask while at the airport, except when eating or drinking, and even then should limit their time unmasked to a minimum.

- Disinfection refers to the deactivation or killing of infectious agents, while cleaning relates to the process of removing visible dirt and particles. Overall, disinfection and cleaning practices at airports are substantial. High-touch surfaces are cleaned frequently, with effective disinfecting agents approved by governmental agencies and reinforced by industry oversight bodies.

- The visibility of enhanced cleaning and disinfection measures supports public confidence in the public health safety of the airport environment. Some airports have or are in the process of obtaining voluntary accreditation or certification of their cleaning and disinfection practices, for example, from the American Association of Airport Executives (AAAE) partnership with the Global Biorisk Advisory Council (GBAC) or from the Airports Council International (ACI).

- Enhanced surface disinfection by hand using U.S. Environmental Protection Agency (EPA)-approved cleaning agents has a similar effectiveness in reducing SARS-CoV-2 infections when compared to more sophisticated systems like electrostatic spraying and high energy ultraviolet (UV)-C (222 nanometers [nm]/254 nm) disinfection. The difference between these options is in equipment investment, time required to disinfect large-areas, levels of staffing, and personnel training requirements. A careful analysis considering this information and overall effectiveness goals should be performed before investing in new technologies.

- Ultra-violet radiation (FAR-UVC; 207 – 222 nm) might be suitable for continuous surface disinfection in queues, food courts, bars, restaurants, store counters, security checkpoint bins and other surfaces typically found in airports. FAR-UV disinfection can be a complement to, but is not a replacement for, surface disinfection.

- While there is a low probability of being infected via fomites in an airport, especially since transmission of SARS-CoV-2 is mostly airborne, as a continued precaution disinfection and cleaning should continue to be frequent and comprehensive.

- It is recommended that hands be disinfected after touching door handles, elevator buttons, faucets, self-service kiosks, point-of-sale keypads, and luggage carts as SARS-CoV-2 might still survive for approximately two to four hours on people's hands.

- Visual and audible signaling to maintain physical distancing and crowd control are easy to display, relatively inexpensive and effective in encouraging behaviors that reduce the risks of COVID-19 transmission. Airports began using these communications techniques early in the pandemic.

- To explore the risk reduction potential of the layered NPI approach in various areas encountered during the Curb-to-Curb journey, a Monte Carlo analysis was undertaken to compare a base-case, an enhanced-case, and an augmented-case across five segments in the Curb-to-Curb journey, namely: check-in area; security checkpoint; airport shops; eating (dine-in restaurants, fast-food restaurants, food courts, etc.), and boarding gates. The base-case scenario generally represented the conditions that existed in these segments at airport terminal buildings prior to airports putting in place the different NPIs to respond to the COVID-19 pandemic. The enhanced-case scenario largely represented the application of a set of NPIs relatively typical of those being employed by airports in response to the current pandemic. The augmented-case scenario represents maximally applied NPI under optimal conditions unlikely to be achievable over time in a real-world setting. For all segments, there was significant risk reduction between the base-case and enhanced-case scenarios, i.e., showing the effectiveness of a layered NPI strategy. However, there was only a marginal difference between the enhanced- and augmented-case scenarios. This analysis can be helpful for airport operators in determining return on risk mitigation investments.

1.2.3 Chapter 5: Viral Testing

- In the setting of air travel, viral testing should be viewed as a public health screening measure rather than a diagnostic clinical tool, with the more limited but important goal of identifying infected travelers and keeping them out of airports and off the aircraft.

- The high sensitivity of reverse transcriptase polymerase chain reaction (RT-PCR) tests for SARS-CoV-2 mean it may not be ideal for public health screening, for example in situations where permission to board a flight is based upon such a test. This is because RT-PCR tests do not distinguish between replicating virus (i.e., the person is infectious) and the presence of remnants of viral ribonucleic acid/deoxyribonucleic acid (RNA/DNA) that will be present even after an infected person is no longer infectious.

- To answer the question, "Is this individual infectious now?", which is highly relevant to air travel, appropriate antigen tests provide that answer quickly. The antigen tests are not only faster, but also sensitive enough to reflect active virus. Given the primary goal is to reduce individual-level risk during travel, pre-travel testing should be performed as close to the travel event as possible, namely the same day or one-day prior, using a test with appropriate sensitivity and specificity.

- Harmonization of testing protocols and requirements is critical to restoring passenger confidence in air travel. This harmonization should be a collaborative undertaking by national governments with their public health services.

1.2.4 Chapter 6: Health Screening

- For travel by air, as with other public-facing activities during a pandemic, a self-assessment of health status should start *before* a person leaves their home; it is a critical component of an effective layered risk mitigation strategy.

- It is unlikely that body temperature screening for COVID-19 in airport settings will be useful to risk mitigation due to limits in sensitivity. The same is true for other potential screening methods considered, such as measuring decreases in oxygen saturation and changes in olfaction (smell) or gustation (taste) sensations.

- Canine sensing is being explored in some airport settings with dogs trained to detect volatile organic compounds produced by COVID-19 through the odor from sweat, tracheobronchial secretions, urine, or saliva. However, there are considerable logistical issues to be overcome before this would be useful in routine practice.

- A new research avenue being explored is the use of artificial intelligence (AI) to compare the coughs, spoken words (in different languages), and respiration patterns of COVID-19 infected people with those of healthy people. Small differences in the way healthy and infected people cough have been shown in laboratory settings and may support the development of a new screening approach.

1.2.5 Chapter 7: Engineering and Physical Controls

- Given the airborne transmission route of the SARS-CoV-2 virus and the COVID-19 pandemic, airport ventilation systems can be adapted to reduce transmission risks. Ventilation systems used in airport terminal buildings typically have not been designed to mitigate the airborne spread of respiratory pathogens. Additional functionality may be required to augment the capacities of existing systems when appropriate physical distancing cannot be maintained, and/or there is insufficient mixing, dilution and removal of air in the immediate area.

- As the World Health Organization (WHO) and the CDC have confirmed the potential for aerosol transmission of SARS-CoV-2, it is imperative that airport heating, ventilation and air-conditioning (HVAC) systems operate at a performance level that will maximize protection from transmission. It is recommended that a qualified HVAC engineering professional audit the airport air handling system and its control settings.

- In areas where passengers tend to congregate and physical distancing of 6 feet (1.83 meters) is difficult or not possible to maintain, airport ventilation systems need to be capable of delivering more than six air changes per hour (ACH) to travelers' breathing zones during these times. The number of ACH that are appropriate for comfort needs may be insufficient to protect against airborne infections, especially in congested areas.

- Given there is yet little or no evidence of SARS-CoV-2 transmission through recirculated or mechanical air systems with long ductwork runs and adequate filtration, it can be assumed that the supply air is virtually virus free and will not introduce an infectious dose to the spaces being ventilated. Therefore, increasing airflow to promote dilution and mechanical removal are reasonable adjustments. Given airport terminals typically have high ceilings and large volume spaces, dilution can be achieved as long as the air is well mixed.

- Airports should consider installing automatic sensors to detect excessive congestion of passengers to allow for the rapid adjustment of air supply to those areas. Adding carbon dioxide (CO_2) sensors in the areas of concern may be an appropriate strategy.

- Eating in the gate holding areas or other places where crowding can occur, such as security queues, should be strongly discouraged. Otherwise, six-plus ACH may be inadequate to prevent potential exposure to infectious doses. If passengers unmask to eat in crowded areas, then virus-shedding rates could increase, resulting in the potential for near-field exposures.

- Supplemental air cleaning and enhanced mixing of air should be evaluated for areas where passengers might congregate in close proximity for a period of 15 minutes or more. Properly sized portable air purifiers and upper room UV-C lamps will increase effective air exchange and support dilution and removal of any pathogens including SARS-CoV-2.

- Similarly, supplemental air cleaning should be considered for break rooms for security, customs, airport, airline and other employees, especially if those areas are used to eat and interact socially.

- A key objective should be to maintain transmission risk below 1% for passengers on airport transport vehicles. The detailed modeling analysis performed on a limited number of exemplar vehicles assumed the vehicles (airside buses, smaller shuttle buses and terminal train) had their ventilation set at maximum, according to the manufacturer's specification, and that one single infectious passenger was onboard the vehicle shedding at a modestly high quanta/hour rate. The results showed that all passengers should be masked, and passengers and loads typically limited to 50% or less for a duration of no longer than 15 minutes. Of course, there are many different vehicle configurations and ventilation rates in use in airport transport. Airport operators should evaluate their fleets and implement appropriate recommendations to maintain transmission risk below 1%.

- Installing physical barriers such as plastic barriers at customer facing service areas and passenger queuing areas can reduce the spread of exhaled virus plumes, but they must be appropriately designed, sized and ventilated to achieve their specific control goal. Detailed simulations demonstrate that installation of plastic barriers can create a 'microenvironment' that could reduce air exchange effectiveness of the existing ventilation system in certain areas.

- Plastic barriers to separate lines where passengers are queueing at check-in, security checkpoints or immigration/customs inspection are not recommended without detailed analysis of the adequacy of air exchange and mixing of air in the breathing zones of passengers. Partitions might create plastic 'canyons' that inhibit airflow. While these barriers might offer some protection to others waiting in adjacent lines, a passenger in front or behind an infectious person is likely to experience concentrations higher than they would have in an open well-mixed space. The analysis supporting this finding assumed 8-foot partitions in a security area with 12-foot ceilings; this might well be a worst-case scenario. Spaces like departure lobbies with higher ceilings and good vertical air mixing might mitigate concerns for restricted airflow in these plastic-sided queues.

- Installation of disinfection devices in air ducts is not recommended at this time. While many commercially available devices claim to disinfect supply air effectively, efficacy needs to be demonstrated through independent third-party verification before adoption. Furthermore, there are no peer-reviewed published case studies to support airborne transmission of SARS-CoV-2 through typical central mechanical ventilation systems.

- Under no circumstances should disinfecting devices that emit ozone into the air be used in occupied settings. Ozone is a strong oxidizing molecule that can damage respiratory systems, irritate mucus membranes, and cause asthmatic symptoms at elevated concentrations.

- Modeling tools are available to help airport operators assess ventilation and passenger management strategies to reduce the risk of airborne viral transmission. Some calculations are straightforward and can be done by facility managers to evaluate specific spaces, like break rooms. For use in more complex open contiguous spaces at an airport, selecting the most appropriate model and its application may require assistance from professionals who understand building systems and COVID-19 risk model applications and limitations. These tools can provide guidance on operating existing HVAC systems, and determining when supplemental air cleaning may be needed. Further, some models can be used in a dynamic sense to inform airport management on how to enhance ventilation mitigation measures and those that manage passenger behaviors. Models that are more sophisticated can incorporate real time sensor data (e.g., CO_2, occupancy sensors) to improve risk-reducing ventilation strategies.

- Passengers, and to some extent employees working at an airport, have sufficient autonomy to reasonably manage their exposure risk. For example, a passenger is not compelled to crowd around the gate at boarding time and can move away from fellow passengers who are unmasked and eating nearby. Eating at an airport restaurant will be an optional activity for most. Cognizant of activities that diminish distances between passengers, a traveler might reduce the time in close quarters with others through reasonable adjustments of their own behavior where residual risk remains.

The findings and recommendations in this report show it is possible to implement various complementary strategies that can be layered to mitigate the risk of transmission of SARS-CoV-2 at airports. Following the science and acting upon it can enhance public health safety.

2.0 INTRODUCTION

The Harvard T.H. Chan School of Public Health Aviation Public Health Initiative (APHI) Phase Two Report continues to examine risk mitigation for SARS-CoV-2. This report focuses on the traveler's journey whether departing, arriving, or connecting (including any inter-airport transfers), designated as the '**Curb-to-Curb**' portion of travel. The Report considers passenger activities from the point at which they arrive at the airport terminal, curbside or entrance, and includes check-in, baggage drop-off, security screening, concessions, support facilities (such as dining, shopping, and restrooms), and departure hold rooms at the gate area before entering the jetway to board the aircraft. After the flight, the Curb-to-Curb traveler journey continues from the point the passenger disembarks the jetway and enters the terminal building, passes through customs (in the United States, U.S. Customs and Border Protection (CBP)) checkpoints where appropriate, baggage claim, and leaves the terminal. Once airside, the use of buses, trams, trains, etc. are included as part of the traveler's intra-airport (between terminals and gates) journey; however, travel to and from the airport is excluded. The aircraft portion of the journey was reviewed in the Phase One 'Gate-to-Gate' report (Harvard APHI, 2020).

While the NPI framework for assessing and mitigating risk of SARS-CoV-2 transmission is similar for both the airport and the aircraft phases, there are some important differences. For example, once onboard the aircraft, passenger movements are restricted and can be monitored, people are seated and mostly facing the same direction and the ventilation system is designed to filter, dilute and rapidly remove contaminants from the breathing zone. In contrast, in an airport, passengers are relatively free to move around and undertake a range of activities, such as checking-in, dropping off baggage, going through security check, and queuing in the gate area. They may also spend time in one of the concessionaires, choose to dine at a restaurant or bar (depending on restrictions that may be in place from state and local authorities), shop at one of the stores, use the restrooms, or relax in one of the lounge areas. Travelers spend time in different physical spaces within the airport for varying amounts of time. Diverse airport layouts affect ventilation rates and congestion, with airline schedules and daily/seasonal travel cycles influencing passenger numbers. Given these considerations, **the airport environment is much more complex when it comes to studying SARS-CoV-2 transmission risks and mitigation efforts**.

Figure 2.1 shows the basic functional components found at most commercial airports. These areas are configured differently at different airports, often a function of the size of the facility and the volume of passenger traffic. Therefore, while airports may offer similar functions there are no two airports, and generally no two terminals, that are truly alike. For a passenger *departing* from an airport, there are a number of required processing areas where delays and congestion can occur, such as check-in, checking baggage, security checkpoints (in the U.S., Transportation Security Administration (TSA)), departure gate waiting areas, etc. For a passenger *arriving* at an airport, transit times are usually less than the processing times for a passenger preparing to depart. Of course, there are potential areas of congestion e.g., waiting at baggage carousels and processing through customs if required.

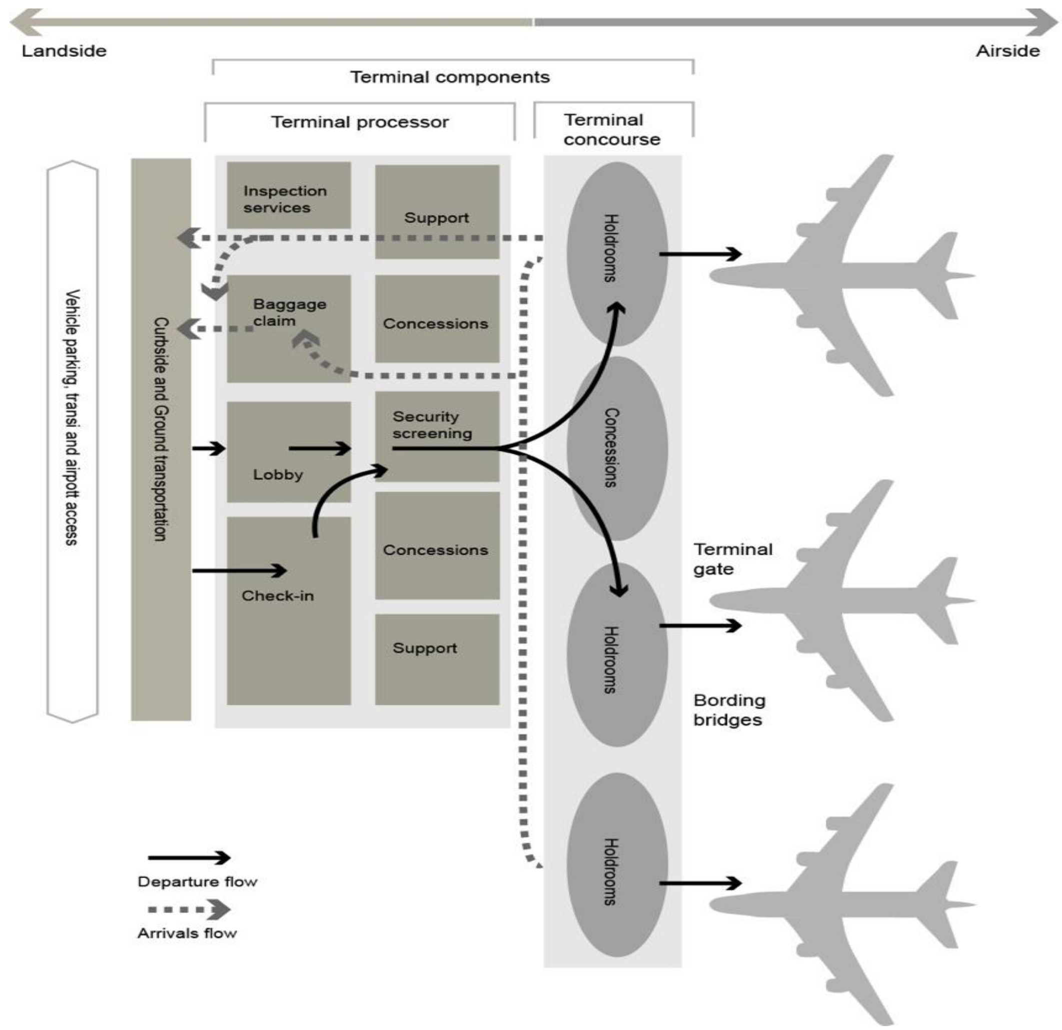

Figure 2.1 Schematic of the Components of an Airport Terminal. (Adapted from FAA, 2018)

Airports are the type of locations where transmission (direct contact via droplets, airborne transmission by aerosols and contamination of surfaces) may occur. Recognizing some airport spaces are restricted to ticketed passengers only, large volumes of people traverse the airport with some spaces periodically congested. As such, airports are therefore focusing on mitigating risks through a range of measures from cleaning and disinfection, to promoting compliance with wearing face coverings/masks, encouraging physical distancing and upgrades to ventilation (see Chapter 3). Risk of direct droplet contact or airborne transmission across these nodes will depend on the probability of inoculating a person's respiratory tract with a critical dose of SARS-CoV-2 virus. This in turn is a function of proximity to an infectious individual, viral emission rate in the vicinity of the subject, exposure time, breathing rate, implementation of individual mitigation measures (e.g., wearing of face masks) and the ability of the ventilation system to disperse, dilute and remove pathogens. Given the complexity of space within an airport, the various functions undertaken and different user interactions, the Aviation Public Health Initiative Science and Technology (S&T) team made decisions on how best to frame a physical assessment of airports. In addition, the team factored in which airport functions to assess in developing the risk assessment and stratified mitigation measures for effectively addressing the SARS-CoV-2 virus. The following scheme is appropriate for the Curb-to-Curb project:

People: The focus of this report is on passengers using airport facilities across a 'typical' trip in the manner common to economy class customers. Passengers with special status who might enjoy shorter processing time through security or customs or avoid crowded gate areas by using lounges and/or boarding first were not considered separately. Employees of airports, airlines, security, customs and immigration, concessionaires and others who work on airport property typically spend a longer time inside an airport and use other spaces compared to a typical passenger. Where appropriate, any relevant differences in risk among employee settings are highlighted. Ventilation and disinfection strategies to reduce the risk of viral transmission among passengers also benefit those who work at airports. Employers, in most cases, have already deployed physical barriers to protect those workers in face-to-face contact with passengers. Whether by state or local requirements, airport operators require all employees, service contractors, maintenance staff and workers to wear approved face coverings/masks properly.

Airport Operations: Airports employ a variety of governance structures with implications for jurisdiction, organization, and management. State or municipal authorities operate some airports directly, while others are managed privately. The responsibility for managing specific spaces and functions within an airport also varies. For example, in international airports located in the U.S. CBP will have jurisdiction over their spaces and typically, this will be the same for the TSA. Though rare, at some airports, airlines own and operate their own terminals. However, the utilities serving these spaces (lighting, ventilation etc.) are often the responsibility of the airport facility management. Air carriers, like concessionaires, typically lease and control their own spaces, within certain limits imposed by their leases. Airports and their leaseholders' response to handling the COVID-19 situation may vary. In some cases, state or city jurisdiction over an airport will mandate face covering/mask wearing and cleaning practices throughout the facility. In others, airlines, shops, restaurants and other concessionaires have more discretion with respect to implementing risk mitigation measures. Hence, one of the reasons for the phrase, "If you've seen one airport, you've seen one airport."

Airport Boundary: For the Curb-to-Curb traveler journey, it is necessary to determine where the 'curb' begins and ends. Airports in the U.S. and around the world use a strict physical definition that is bounded by the airport terminal entrance and the public side of an airport building exit. This is the focus of this report. It would not include adjacent parking lots, shuttle or taxi areas, attached hotels or car rental areas. However, given the complexity of airport operations there are some critical transportation functions that serve as important links to the terminal buildings and may extend the ’curb-to-curb‘ definition in those limited cases. For example, some airports are responsible for buses and coaches that seat >30 passengers and smaller shuttle buses that seat around 15 passengers; these are used for transporting passengers and staff between terminals and to offsite locations. Buses used to transport passengers airside to/from gates to airplanes docked at remote stands are included here because they present potential risk related to transmission of SARS-CoV-2 within the bounds of the airport’s responsibilities.

Unlike commercial aircraft, for which the basic design, configuration and operational capabilities are similar, airports are heterogeneous in architecture and management. To deal with the complexity of airports, this report adopts **the ‘layered approach’ to risk mitigation**, namely the application of multiple **Non-Pharmaceutical Interventions** (NPI) to help reduce potential risk of SARS-CoV-2 transmission. In evaluating the NPIs as they apply to the ‘Curb-to-Curb’ airport environment, the report builds upon the Phase One ‘Gate-to-Gate’ report for aircraft (Harvard APHI, 2020).

Non-Pharmaceutical Interventions (NPI) are actions that can be implemented to slow and/or limit the spread of infections amongst a population (see Figure 2.2). NPI can offer a level of protection for those at risk of illness upon infection by infectious organisms – in this case the SARS-CoV-2 virus. NPI measures fall into three general categories, namely:

1. **Personal:** These include routine personal hygiene measures, such as hand washing with soap. Also included are use of hand sanitizer, practicing cough/sneeze hygiene and wearing face-coverings such as masks.

2. **Community:** These include policies and strategies aimed at the community level to raise awareness about the disease and how it is spread. For example, educating people about steps they can take to minimize the risk of transmission, such as not travelling when they feel unwell, adopting physical distancing in situations where they might normally be in close proximity to other people, and encouraging them to make efforts to minimize exposure to any known high risk populations.

3. **Environmental:** These include practices and procedures that seek to limit viral exposure, for example promoting cough/sneeze hygiene and the routine cleaning of surfaces to help reduce any viral contamination on surfaces and objects. Also included in this category are ways in which an environment might be manipulated, for example by increasing ventilation.

Combining elements of personal, community, environmental NPI provides a **layered approach** that seeks to capture the additive or synergistic risk mitigation effects of each intervention. The different layers of NPI are categorized as: Education and Awareness; Screening; Physical and Engineering Controls; Process Management, and Personal and Protective Equipment (PPE). Within these categories, various operational and programmatic controls have been identified that can be implemented. Figure 2.2 outlines various control measures for each category and how they might be integrated to provide the layered protection afforded by a systematic integration of NPIs.

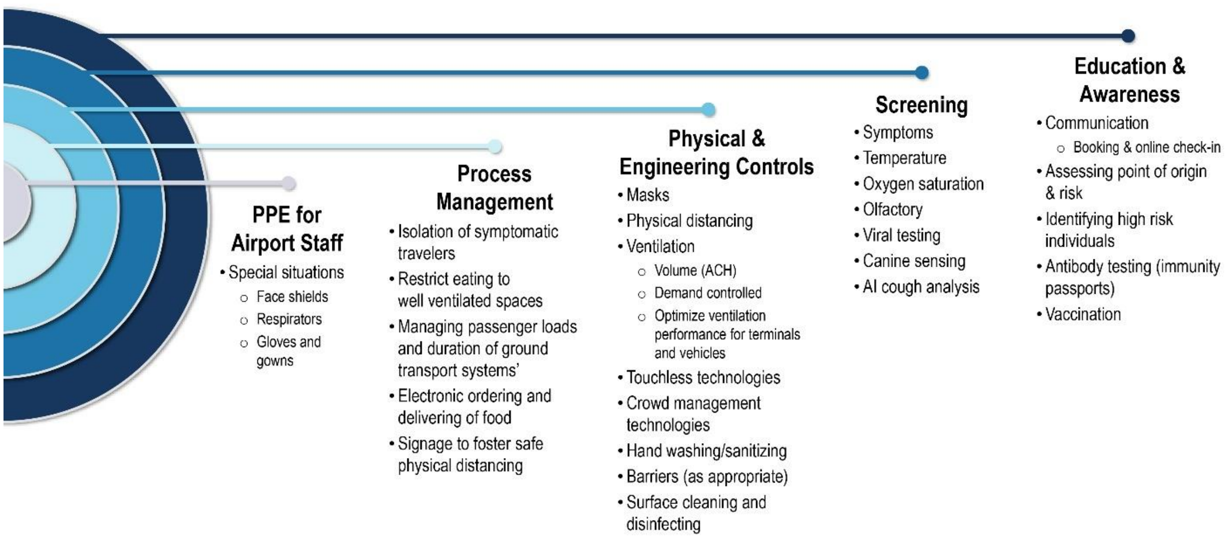

Figure 2.2 The Layered Approach for Disease Mitigation Strategy using Non-Pharmaceutical Interventions

Modeling and measurement studies consistently support the assertion that applying multiple NPI across the different levels of control as shown in Figure 2.2 can be highly effective at reducing the spread of SARS-CoV-2 (Cowling et al., 2020). **Those seeking to reduce the spread of SARS-CoV-2 should consider the NPI proposed here as a system of interlinked risk mitigation interventions that when used together can effectively control the risk of exposure to the novel coronavirus during all phases of air travel.**

Context specific information on behavioral aspects is also explored. **Chapter 3** builds on the primary research conducted in the study, encompassing data collated from questionnaires (see Appendix F) completed by airport management teams across 25 airports (23 from the U.S., two from elsewhere), and interviews with six selected U.S. airports. Interviews with TSA and CBP and two representative industry bodies gathered further information. Material on building systems and operational management structures was gathered through two site visits to U.S. airports undertaken by the S&T team and led by airport personnel. **Chapter 4** updates information on face masks and cleaning and disinfection relevant to terminals. **Chapter 5** provides a detailed account of viral testing and diagnostic tools related to viral load assessment. **Chapter 6** presents health screening opportunities as they apply to airport operations, including use of innovative approaches to COVID-19 screening now being assessed, ranging from canine detection to use of Artificial Intelligence (AI) to assess recordings of coughs from COVID-19 cases.

The visits to two U.S. airports supported assessment of the ventilation strategies and is presented in **Chapter 7**. Given airport complexities, in both architecture and operations, generalized advice on this critical element is provided based on comprehensive modelling studies undertaken by the S&T team, composed of Harvard faculty and research scientists. Together with knowledge of building systems, the efficacy of ventilation-based strategies was determined. Using well-established mathematical constructs, airflows and air exchange rates along with mixing, dilution and removal of contaminants, models were developed to assess risk at predetermined 'choke' points where passengers may congregate thereby limiting physical distancing. While it is clearly not possible to model all variants, the modeling exercises provide a comparative risk analysis among the different activities and locations most passengers are expected to experience while at an airport. By modeling transmission risk, it was possible to anticipate how introducing supplemental air cleaning efforts could have positive and negative implications. In addition to modeling selective 'choke' points inside airports, analysis was conducted of how airport bus, shuttle and train ventilation systems influence the risk of transmission. Table 2.1 highlights potential 'choke' points that can occur during the course of heavy passenger traffic and at times of disrupted services that necessitate greater reliance on engineering control strategies. Overall, the Phase Two report includes information secured through the questionnaires, interviews, field visits, and customized modelling studies, that together with a critical literature review inform its recommendations, with concluding remarks given in **Chapter 8**.

Table 2.1 Areas of Potential Concern
Check-In Lines and Bag Drop Off
Security Lines
Restaurants, Bars-Unmasked For Eating and Drinking
Cluster of Gates and Holding Areas Waiting for Boarding
Immigration A and Customs
Luggage Retrieval with Multiple Arrivals
Transport—Intra-Airport Buses and Trains

2.1 LINK TO PHASE ONE REPORT

Since release of the APHI Phase One Report in October 2020 (Harvard APHI, 2020), the scientific understanding of the SARS-CoV-2 virus and COVID-19 has progressed. Infection rates have surged worldwide, more than doubling across the U.S., and more young people have become infected. While improved treatment regimens and the younger patient cases have lowered fatality rates, COVID-19 is now the leading cause of death in the U.S. (Woolf, 2020). Worldwide scientific research by universities and pharmaceutical companies has developed a suite of vaccine candidates in record time, with Operation Warp Speed (HHS, 2020) making vaccines available in the U.S. to millions of health care workers, critical service professionals and the most vulnerable populations. The U.S. Federal Drug Administration gave the first SARS-CoV-2 vaccine emergency use approval on December 11, 2020 (FDA, 2020a; FDA, 2020b), with the first person in the U.S. vaccinated against COVID-19 just three days later (Otterman, 2020) and a second vaccine candidate approved that same week. While public confidence in the vaccine is increasing, about 50 to 70 % of the population remained wary at the end of December 2020 (Azimi et al., 2020). This is important as herd immunity is thought to require 73 to 84% coverage in a population (Ke et al., 2020). Health experts state that vaccination offers protection against developing COVID-19 associated symptoms but does not necessarily prevent a person from becoming infected or transmitting it to others (CDC, 2021). **Therefore, maintaining public health protective protocols remains an imperative – namely, wearing a face covering/mask appropriately, practicing proper hand hygiene and maintaining physical distancing where possible.**

By early December 2020, new insights about the relative importance of transmission by fomites, droplets and aerosols emerged. For fomite transmission, picking up a sufficient quantity of SARS-CoV-2 from a contaminated surface and then transferring a critical amount of virus to a mucosal area on the face was deemed less likely to occur outside of a healthcare or home setting (Mondelli et al., 2020; Goldman, 2020). For droplet transmission, close proximity to an infectious person is a well-accepted mode of transmission. Recently, the CDC and the World Health Organization (WHO) recognized the important role smaller aerosols suspended in the air play in COVID-19 infections (CDC, 2020; WHO, 2020). **The CDC now recommends enhanced ventilation (in some settings) as an important component of a layered approach to mitigate the risk of transmission of SARS-CoV-2** (CDC, 2020).

The importance of ventilation onboard an aircraft was highlighted in the Phase One Report, noting how ventilation systems served a critical role in dispersing and removing any exhaled contagions in aerosols (Harvard APHI, 2020). The aircraft environmental control systems (ECS) are designed to meet demanding flight conditions. In contrast, airport terminal buildings typically have conventional mechanical air handling systems similar to heating, ventilating, and air-conditioning (HVAC) systems used in offices, hotels, theaters, and shopping malls. Airports are normally large open contiguous spaces that experience significant fluctuations in both occupancy and thermal loads. They are subject to design considerations that are substantially different from other indoor settings. Therefore, this study explores **the opportunity for ventilation improvements in airport terminal buildings to be used as an additional mitigation strategy** (see Chapter 7).

This Phase Two report on airport operations refers to the scientific evidence supporting the mitigation strategies of masking, disinfection and physical separation presented in the Phase One report. Where appropriate, these NPI are updated or contextualized to an airport terminal setting. This report also includes new information not fully explored in Phase One. For example, it includes information about pre-flight passenger and employee screening, including those conducted in airport terminal settings where new technologies and testing have the potential to reduce the risk of an infectious passenger boarding a plane. Rapid virus antigen and molecular tests are already in use in some settings, including at some airports. **It is however beyond the scope of this Curb-to-Curb analysis to recommend risk mitigation approaches for any particular airport given the wide variety of airport sizes, architectures, layouts, functions, and management structures.**

2.2 BACKGROUND ON COVID-19

Understanding SARS-CoV-2 and its behavior are important to the aviation industry so that it can best develop strategies and direct its activities to reduce potential spread of the virus. It is also important that the aviation industry avoids implementing any unproven measures that are of limited or no material effect in reducing viral transmission or that might even increase risk (see Chapters 4 and 7).

COVID-19 is an infectious respiratory disease caused by the virus SARS-CoV-2. It was first recognized in December 2019, when an outbreak of a new type of coronavirus occurred in the province of Hubei, China. The outbreak spread very rapidly, affecting most countries worldwide and was declared by the WHO on January 30, 2020 as a Public Health Emergency of International Concern (PHEIC) (WHO, 2020a). By March 11, 2020, it was designated a pandemic (WHO, 2020b). As of December 13, 2020, there were 71.9 million cases and over 1.5 million deaths worldwide, with many millions still suffering severe illness and economic hardship (JHU, 2020). Key characteristics of the virus, variants, and the way it is transmitted are described in the following sections as background to understanding science-based approaches to reducing its spread and creating safer environments.

2.2.1 Background on SARS-CoV-2 Virology

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is the causative agent of CoV disease 2019 (COVID-19) (Ludwig & Zarbock, 2020). SARS-CoV-2 is a member of the

Coronaviridae family in the subfamily *Coronavirinae*. Based on genetic and phylogenetic relationships, this subfamily is classified into four genera: α-, β-, γ-, and δ-CoV. Members of the α- and β-CoV genera infect mammals (Ye et al., 2020). Currently, circulating CoVs in the human population include two α-CoVs and two β-CoVs that cause the common cold (Ye et al., 2020). SARS-CoV-2 is a β-CoV (Ye et al., 2020). Variants of SARS-CoV-2 are emerging, some of which appear to be more contagious; however, there is nothing yet to suggest they cause worse disease or that they might evade some of the protection afforded by a COVID-19 vaccine (CDC, 2020). Several other highly pathogenic human β-CoVs have emerged in the past two decades, namely SARS-CoV-1 and the Middle Eastern respiratory syndrome coronavirus (MERS-CoV) (Ye et al., 2020). Human-to-human transmission via direct or indirect contact and inhalation of respiratory droplets are the main modes of spread of highly pathogenic CoVs viruses (Cui 2019; Neerukonda & Katneni, 2020).

SARS-CoV-2 virions are spherical, with a diameter of 60-100 nanometers (nm) conforming to the typical CoV diameter of 125 nm (Jin et al., 2020). CoVs are named after their crown-like morphology, as observed under the electron microscope, afforded by the surface glycoproteins on the virus. They are enveloped positive-sense single-stranded RNA viruses that can cause a wide range of respiratory, enteric (gut), hepatic (liver), renal (kidney), and neurologic diseases in mammals and birds. SARS-CoV-2 gains entry into human cells to replicate itself via the human angiotensin-converting enzyme 2 (ACE2) receptor (Hoffman, 2020). ACE2 is a type I membrane glycoprotein found on cells in the lungs, heart, intestines, and kidneys (Yan et al., 2020). Following transmission, the virus replicates inside cells of the respiratory (upper and lower) and gastrointestinal tracts. There is also recent evidence of neurological disruption by damaging neurons in the central nervous system (Xu & Lazartigues, 2020).

2.3 ROUTES OF TRANSMISSION

2.3.1 Means of SARS-CoV-2 Direct Viral Transmission

SARS-CoV-2 is transmitted from person-to-person when respiratory droplets containing the virus are expelled from a contagious person while breathing, vocalizing, coughing, and/or sneezing and subsequently taken up through the mouth, nose, or eyes of a non-infected person; the virus then generally deposits on the lining of the nasal passages or throat (Sungnak et al., 2020; Zhang et al., 2020). Three possible pathways of transmission are recognized:

1. Close contact transmission can occur when an infectious person sheds droplets and aerosols that come into direct contact with an uninfected person’s mucus membranes of the eyes, nose and/or mouth or are inhaled by that person. As a term, ‘close’, is considered to be within 6-feet (1.83 meters). There is convincing evidence of SARS-CoV-2 transmission via droplet and aerosol transmission when people are in close contact (CDC, 2020a). Practices that

distance people from one another and wearing face masks are risk mitigation responses to this mode of transmission.

2. Fomites (i.e., objects contaminated with infectious agents) transmission can occur when infectious particles that have previously become deposited on inanimate objects or surrounding surfaces via airborne droplets or through direct contact with other contaminated surfaces, such as hands and/or tissues, are subsequently transferred to the membranes of the eyes, nose and/or mouth and transfers disease to a new host. While very few cases of fomite transmission have been reported (Goldman, 2020; Meyerowitz et al., 2020), this route does not require physical proximity to the infectious person. **Transmission by fomites occurs much less often than via close contact.** Practices that clean and disinfect surfaces thoroughly are means to mitigate this form of transmission.

3. Longer-range or airborne transmission refers to the exchange of small, microscopic respiratory droplets that can remain suspended in the air, allowing for subsequent inhalation by an uninfected person; this is widely referred to as aerosol, or long-range transmission. Some reports of spread between people in crowded, indoor settings with poor ventilation are consistent with transmission via aerosols (WHO, 2020). These cases might also be explained by undocumented close contact (Cirico et al., 2020). Long-range transmission is thought to occur less often than large droplet or aerosol transmission by close contact. Practices that utilize wearing a face mask and the provision of highly effective ventilation and air filtration are designed to mitigate disease spread through this mode of transmission.

2.4 SECONDARY TRANSMISSION—WHERE DOES SECONDARY TRANSMISSION OCCUR?

Secondary transmission of SARS-CoV-2 refers to the situation in which a case of COVID-19 can be traced back to a primary infected person, whether that person is pre-symptomatic, symptomatic or asymptomatic; the lack of symptoms in the primary case can hinder the ability to detect possible exposure to the virus (Bae et al., 2020; Rothe et al., 2020; Tong et al., 2020; Zhang et al., 2020). Identifying incidents of COVID-19 transmission is further complicated by differential exposure times, the viral shedding rate of infected individuals, compliance with wearing a face mask, viral survival times on fomites, proximity to other individuals and physical conditions of the environment (temperature, humidity, and ventilation levels (Anderson et al, 2020; Asadi et al., 2020; Ganyani et al., 2020; Prather et al., 2020; van Doremalen et al., 2020)). However, there are some factors common to secondary transmission:

- Low physical distancing between individuals in low ventilation situations and poor community compliance with face mask-wearing increase COVID-19 infection rates in different environments (Aggarwal et al., 2020; Chu et al., 2020; MacIntyre & Wang, 2020).

- The presence of higher levels of infected individuals in the community and in-person gatherings increase secondary transmission of SARS-CoV-2 (Majra, 2020; Quadri, 2020).

- **Most COVID-19 secondary infections occur indoors** in enclosed places such as homes, healthcare facilities, long-term care facilities, penitentiaries, shopping malls, supermarkets, office buildings, factories, restaurants, places of worship, entertainment venues, etc. (Marshall et al., 2020; Quian et al., 2020; Rothe et al., 2020; Shen et al., 2020). Additionally, most super-spreader outbreaks with tens or hundreds of secondary COVID-19 infections occurred indoors (Park et. al, 2020: Phylogenetic Analysis, 2020). For this reason, the airport terminal building – as a unique indoor space with many people from distant locations present for extended periods – deserves focused attention.

Research provides new information on those **environments associated with higher relative risks** of disease transmission. Between 30 to 70% of all secondary COVID-19 infections occur at home (Fink, 2020; Murti et al., 2020; Public Health Seattle, 2020; Shen et al., 2020). Community and social gatherings are responsible for 25 to 40% of all secondary infections; these include get-togethers with family or friends, dinner parties, birthday and other celebrations, holiday parties, weddings, and visiting food service establishments, retail locations, places of worship, and other venues (Public Health Seattle, 2020; Saidan et al., 2020; Yusef et al., 2020). Workplace gatherings account for 20 to 35% of all reported secondary COVID-19 cases (Bui et al., 2020; CDC, 2020a; Public Health Seattle, 2020; WSDH, 2020). All forms of travel combined represent between 5 and 10% of all reported secondary cases. However, these are mainly ground-related secondary transmissions as the rates of infection inside an aircraft are extremely low due to high ventilation rates, the universal use of face masks and High Efficiency Particulate Air (HEPA) filters that remove at least 99.9% of virus aerosols inside an air cabin (Silcott et al., 2020; Harvard APHI, 2020). In the absence central reporting or tracing of secondary infections, local and state authorities have taken it upon themselves to report on this. The King's County WA, U.S. summary (Figure 2.3 and Appendix B is one such example (Public Health Seattle, 2020). Recognizing its limitations, as it relates to one U.S. city, it does serve to illustrate potential exposure settings for risk of secondary transmission identified among COVID-19 cases and is instructive in showing where these infections may be occurring.

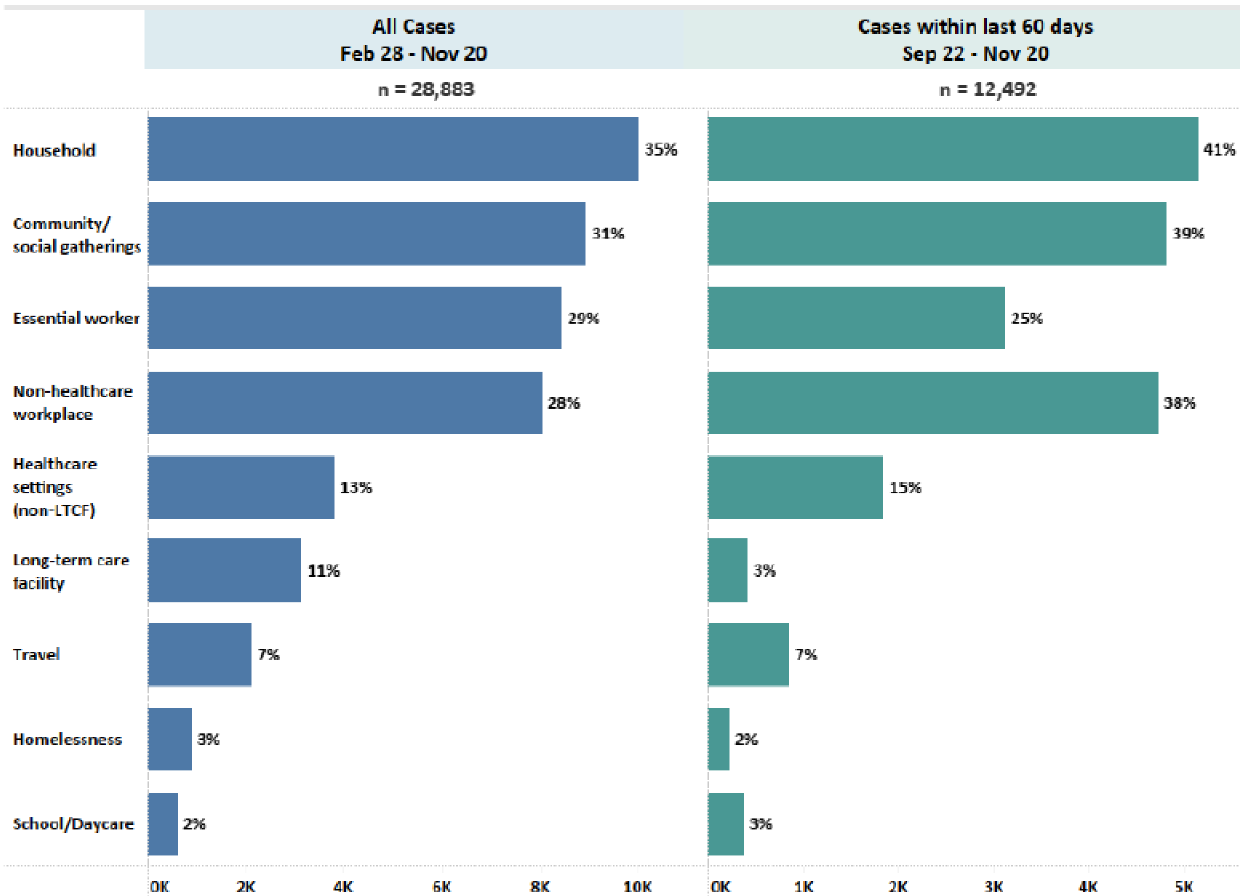

Figure 2.3 All Potential Exposure Settings Identified Among COVID-19 Cases in King County, WA (Public Health Seattle, 2020)

A **breakdown of infections by different occupational groups** can be a useful proxy to identify some of the higher risk places to contract COVID-19 outside of the home. For that reason, several government entities compile records on occupational cases by industry or sector (Bui et al., 2020; Marshall et al., 2020; Public Health Seattle, 2020). According to records in North America, the highest occupational risks for COVID-19 are among healthcare workers with 10 to 25% of all cases (CDC, 2020a; Marshall et al., 2020; Schwartz et al., 2020; WSDH, 2020). This is followed by security and social assistance workers (correctional facilities, homeless shelters, and long-term care facilities) at 8 to 12% of cases, food production workers (agriculture, fishing and food processing) with 7 to 11% of cases, food service and restaurant workers with 7 to 10% of cases, retail and grocery workers with 6 to 9% of cases and construction workers with 5 to 8% of all cases (CDC, 2020a; Marshall et al., 2020; Schwartz et al., 2020; WSDH, 2020). These economic sectors account for 48 to 72% of all reported secondary COVID-19 workplace infections in the U.S. and Canada (CDC, 2020a; Marshall et al., 2020; Schwartz et al., 2020; WSDH, 2020). A typical statewide breakdown of workplace-related COVID-19 infections in Washington State is shown in Appendix B.

2.4.1 Contact Tracing

Contact tracing includes the identification, monitoring and support of a confirmed or probable case's close contacts. It is a fundamental element of public health infectious disease surveillance. As it relates to air travel, passenger contact information can be used to notify travelers following the identification of an infectious passenger on a flight. In order for a contact tracing system to be effective, there must however be broad surveillance testing in order to quickly identify index cases (WHO, 2020) and a process to comprehensively identify and advise quarantine (Fraser et al., 2004; Hellewell et al., 2020; Keeling et al., 2020).

Barriers to implementing an effective contact tracing program include being able to obtain complete and accurate information from cases. In the case of travel, this can prove to be difficult. Manually contacting people is labor intensive and typically left to under-resourced public health agencies (Keeling et al., 2020). Generally, providing the information needed is voluntary given civil liberty regulations (Clark et al., 2020; Chesney, 2020) and ethical issues related to personal data usage (Parker et al., 2020). Finally, access to large scale, population-wide testing is critical and is lacking in many areas. There is no mandatory U.S.-wide policy for contact tracing, which has left each jurisdiction to implement its own processes creating a confusing landscape for both domestic and international travelers (Clark et al., 2020).

While there are challenges in the U.S., other countries have implemented systems that appear to be effective. For example, in Italy, passengers are required to disclose their contact information for contact tracing purposes (Sauer, 2020). In China and South Korea, travelers are required to download tracking applications (apps) to monitor exposures. This technology can reduce labor requirements by automating the processing of test results or symptom reporting and, by use of smartphone capabilities (e.g., Bluetooth), identify and notify contacts instantaneously who may be at risk of infection (Chan et al., 2020; Ferretti et al., 2020; Lochlainn et al., 2020).

A consistent approach, using technology to alleviate resource issues could be a path forward. Even as the vaccine program progresses, there will still be COVID-19 cases for the near future, and hence a need for contact tracing to minimize the risk of outbreaks. Given the barriers to a nation-wide program, several airlines have announced partnerships with the CDC to voluntarily collect contact information (Delta 2020; United 2020) which could be a model for broader applications.

2.5 BEHAVIORAL FACTORS RELEVANT TO AIRPORTS AND DISEASE TRANSMISSION

The transmission of SARS-CoV-2 intensifies or slows as a function of patterns in human behavior. Curtailing risky behaviors that contribute to viral spread, therefore, is essential to mitigating the pandemic, its attendant anxieties and its economic implications. These individual behaviors include wearing a suitable face covering/mask, physical distancing, and hand hygiene combined with limiting congregation indoors. **Behavioral compliance is a particular challenge in the airport environment.**

Securing compliance is a complex process, especially given the unique features of the COVID-19 crisis. Methods for gaining compliance differ markedly from one jurisdiction to another. While the International Civil Aviation Organization (ICAO) has established aviation sector-wide guidance, with which airports and airlines have sought to comply, the overlay of various federal, state and local authorities and behaviors have resulted in some variations. **Strategies that encourage behavioral compliance are central to countering risks of transmission as people navigate the airport environment.**

COVID-19 pandemic is an unprecedented and unusually long-duration crisis. While the population generally understands and accepts short-term restrictions, such as an evacuation during a hurricane, this crisis has long outlasted the patience required for consistent and continued compliance. The absence of a reasonable remedy that could effectively counter an anxiety-provoking situation downplays the threat itself (Peters et al., 2013). For example, the introduction of vaccines and changes in political leadership are changing the experience and attitudes about the situation. At the same time, viral mutations and new information about the disease add another layer of mystery and fear. A study in Poland investigated the relationships between time perspective and compliance with COVID-19 public health regulations (Sobol et al., 2020). It suggests that public health campaigns should emphasize the "here and now" and the importance of current behaviors for the future.

The COVID-19 pandemic has provided a psychosocial context of subjectivity observable in myth, anxiety, anger, discouragement, loneliness, and desperation. The interactive complexity of these frames the landscape of challenges facing behavior modification. While those who comply seem to outnumber those who defy, the recent spate of Thanksgiving-Christmas-New Year social gatherings sparked record-breaking surges in infections across the country.

Vaccines, political changes, and a deeper understanding of the virus have encouraged some measure of hope and anticipation about resolution of the crisis. However, how, when and to what degree the crisis dissipates is yet unknown. This uncertainty directly impacts the public's attitudes and decisions about when and where to travel and the required behavioral compliance. For example, mask wearing may be universally required on airplanes even well past wide distribution of vaccines. As the pandemic and associated mitigation measures evolve, discerning what would motivate universal behavioral compliance remains a question. **Until mitigating behaviors evolve in step with advances in treatment, technology, and inoculation, the COVID-19 crisis will persist.**

2.5.1 Research on Behavioral Factors During COVID-19

Given the unique behavioral factors relevant to COVID-19, the literature reviewed here focuses primarily on recent studies on the topic and considers psychosocial contributors to compliance.

Jørgensen et al. (2020) conducted a study in eight Western democracies, surveying over 26,000 people about their protective behaviors during the COVID-19 pandemic focusing on two key variables: fear and efficacy. They found, consistent with prior research on epidemics, that "perceptions of threat are crucial and culturally uniform determinants of protective behavior" (Jørgensen et al., 2020). Fear is a motivator. Another factor in compliance is the belief in "knowledge-based efficacy," with people more likely to comply if they believe the recommended actions in fact are protective. This combination – fear and efficacy – can inform campaigns to encourage public compliance.

How does this apply to airport environments? As is the case with many public spaces, COVID-19 has changed the nature of transit through airports. Calling for the current crisis to be viewed through the experience of the passengers, Tuchen et al. (2020) argue, "Airport systems can be made more agile, flexible, and resilient by embedding an understanding of what has happened, is happening, and what might happen in the day-to-day reality into strategic decisions for the future" (Tuchen et al., 2020).

Messaging to promote a culture of safety may improve compliance. A study found that Canadians are significantly more likely to comply with face mask advisories "when doing so is seen as a means to protect others from COVID-19 rather than as a means to protect themselves" (van der Linden & Savoie, 2020). This insight will be particularly important once the vaccination program progresses. Currently available efficacy data indicate that vaccines are very effective at protecting the recipient from serious illness. However, it is unknown at present if vaccinated individuals are still able to spread the virus asymptomatically. Under those circumstances, collective interest will be a key factor in reducing overall disease transmission: Doing so **will require convincing vaccinated people to continue preventative and altruistic behaviors – including wearing face masks and physical distancing – for the duration of the crisis.**

Social identity is another factor that impacts compliance with COVID-19 preventative behaviors (Templeton et al., 2020). This is an important variable for understanding behavioral compliance in an airport, as different groups that pass through the facility vary by ethnicity, political persuasion, or geography also vary in their experience, beliefs, and attitudes about the pandemic. This study reports on "how identity definitions and norms can be counterproductive to safety, as well as how poor leadership can exasperate inequalities and lead to long-term challenges to governance" (Templeton et al., 2020). The authors argue, "to manage disasters safely, it is imperative that governments provide fair and legitimate support to mitigate stigmatization of marginalized groups" (Templeton et al., 2020). These insights are critical in mass disasters, such as COVID-19, in order to encourage universal compliance with preventative strategies among diverse populations.

In keeping with this theme, Bellato (2020) recommends that public health *messaging* focus on three refrains: empathy, positive mood, and social influence. The experience of empathy for others increases adherence to mitigation procedures. Similarly, Bellato notes that “positive mood has been associated with an increased predisposition to carry out pro-social behaviors,” (2020), likewise encouraging compliance. Moreover, the persuasion of respected figures, leaders, and influencers, also enhances compliant behavior. The emphasis is creating a belief system that stresses, “We are all in this together.” Indeed, in reframing the “in-group” to be more inclusive, the reach of such altruism in kind can be extended (Kunst et al., 2015).

The evidence on values and adherence to COVID-19 preventative measures “suggests that human values, and the extent to which they are shared by fellow citizens, are likely to be important factors for tackling the COVID-19 crisis” (Wolf et al., 2020,). Indeed, Wolf and colleagues found those who are more compliant with COVID-19 behavioral guidelines attach higher importance to responsibility and security values, along with a sense of connectedness that may be crucial to promoting collective efforts to contain the pandemic. This perspective encourages messaging that appeals to the underlying values of the public as a means to encourage compliance, in order to embed commitment to these behaviors. For example, an emphasis on the positive and shared benefits of compliance elicits feelings of social connectedness, which are more encouraging than the negative focus on non-compliers.

Van Bavel et al. (2020) provide an extensive overview of social and behavioral science applied to the COVID-19 pandemic response. Reflecting on findings from the Spanish flu 100 years ago, they note three behavioral factors that then deterred prevention: “(i) people do not appreciate the risks they run, (ii) it goes against human nature for people to shut themselves up in rigid isolation as a means of protecting others, and (iii) people often unconsciously act as a continuing danger to themselves and others” (Van Bavel et al., 2020). Remarkably, these considerations still ring true today. Appendix C summarizes their findings on efforts to gain behavioral compliance and includes a more extensive consideration of behavioral factors relevant to airports and disease transmission.

The literature highlights some of the behavioral dilemmas inherent in the COVID-19 situation, derived from the 1918 global pandemic and applicable to the current crisis. Whether or not people comply with disease-eliminating behaviors is a matter of personal choice. It is a voluntary opt-in or opt-out. While governments, employers, and airport operators have some measure of authority to require behavioral compliance, that authority is limited by jurisdictional laws and regulations. Persuading the population to adhere to new behavioral standards demands a mix of fear and efficacy, in which people grasp the VUCA (volatility, uncertainty, complexity, and ambiguity) environment and behave together, in the common interest, exercising personal responsibility in support of shared values. The question is how to achieve this combination of attitudes and behaviors necessary to reduce disease transmission. The findings of the airport surveys, site visits, and interviews conducted for this study offer valuable insights.

2.5.2 The Experience of Airports in Persuading Behavioral Compliance

The airport survey questionnaire, interviews, and site visits reveal that airports sit at the sometimes-contradictory intersection between local attitudes and legal requirements regarding COVID-19 behavior and the uniform practices required by the national and international air transportation system. As discussed in the Phase One "Gate-to-Gate" report of the Aviation Public Health Initiative, airlines require compliance with proper COVID-19 behaviors while on board the aircraft (Harvard APHI, 2020). If passengers refuse, they risk being deplaned or being placed on an airline no-fly list. The message is simple: "If you don't comply, you don't fly." Through these policies, the airlines have achieved overall high compliance with public health protocols. Airline passengers, to some extent, are a captive audience. Airports do not have that same authority and must therefore persuade compliance among the heterogeneous mix of people who traverse their facility.

Based on the survey responses provided by airport operators, there is a consistent and impressive commitment to reduce the risks of disease transmission in their facilities. Elsewhere in this report, there is discussion of their work on cleaning and disinfection, ventilation systems, contactless technology, and physical distancing measures. However, before the recent presidential mandate (Executive Order No. 13, 998, 2021) the lack of federal guidelines to mandate, for example, the wearing of face masks when using public transportation, airport operators were caught between their best intentions and the jurisdictional frameworks in which they operate. The study learned that some large airports straddle different municipalities with different legal requirements, which may in turn differ from their state. This makes it difficult for an airport authority or operator to impose rules that depart from local statute or convention, for example, if a state imposes restrictions on restaurant operations that have unintended consequences such as unmasking in common areas elsewhere (see Chapter 3).

An airport terminal building is a physical space in which a number of different private sector companies conduct business, including the airlines, restaurants, retail establishments, and ground transportation. From the perspective of the airport operator, these multiple entities are largely separate. However, from the passenger viewpoint, this is a single airport experience. Each business may have different employee policies, training, health benefits, and management; some businesses operate locally, though most report to distant headquarters. Therefore, getting all these businesses working together is key to establishing consistency in messaging and practice. A message gleaned from the survey and interviews was, "Though we work for different companies, in this airport, we do COVID together." This includes reporting requirements, so that if an employee of an establishment tests positive, contacts are quarantined and, in most cases, the business closes temporarily. By raising the identity of the airport workforce as a collective challenge, airport leaders hope to embolden a positive sense of community responsibility among business managers and their workforce. As such, the workforce is supported to stay safe and encourage safe behaviors among customers.

The intent of the airport operators is to achieve the highest possible percentage of people in compliance with wearing face masks, physical distancing, and disease preventing hand hygiene behaviors. The first motive is protecting the workforce and the public who transit through their facility. The study revealed a clear sense of pride and accomplishment in the low numbers of airport personnel who have contracted the disease. Beyond that, however, there is also a customer relations and business consideration. Airport management want the facility to convey their commitment to public health safety as a way to assure the travelling public. They recognize that the image of consistent face mask wearing is a proxy for the safety of the facility. The travelling public cannot inspect the inner workings of the ventilation system. However, they can observe the behaviors of other passengers and with that, reach conclusions about their personal safety from infection.

The airport operators surveyed in this study reported that their first line of risk mitigation is *communication*, and an abundance of it. Almost every flat surface, from walls to floors, and digital media like web pages contain ubiquitous COVID-19 directives. Images, warnings, and markings convey the message that proper COVID-19 behaviors are required in the facility. The campaigns include frequent announcements, often offered in multiple languages, and other public communication, including email, text notification, social media, press releases, campaigns, and media engagement. This proactive outreach supports travelers' ability to exercise informed public health choices. According to the airport operators surveyed, raising awareness contributes to high rates of compliance. Often, simply asking people – as one airport called it, the "elective approach" – is sufficient to persuade travelers to opt in to a safe travel environment for themselves and others. Volunteers and employees are dispatched in some facilities to provide travelers with public health information and items such as masks, disinfectant wipes, and hand sanitizer. Several airports reported creating public health "ambassadors" to circulate through the facility and encourage appropriate behaviors. The tone of these messages ranged from requirement – "Everyone in this facility is required to…" – to encouragement – "To keep us all safe together…" The messaging thereby incorporates both a fear/mandate theme as well as an efficacy/safety theme, in accord with the science (Jørgensen et al., 2020). The operators noted that they speak to a wide range of audiences with a mix of motivations and interest in COVID-19 messaging. Therefore, a mix of messages has the highest likelihood of speaking to the wide variety of people and their experiences with the disease.

The surveys also revealed that participants identified two key elements for optimizing public health compliant behaviors. Both speak to what motivates people to maintain behaviors that reduce the risks of disease transmission. The first includes clear, easy to follow instructions based on science. "CDC recommends…" carries weight with the public given that the CDC is a credible, authoritative, and standard source. The second accepts the voluntary nature of compliance. There are limitations on enforcement and a desire to maintain a positive travel experience for those who traverse the facility. Therefore, this side of the campaign focuses on encouraging the desire among travelers to protect themselves and others. It also appeals to community norms, and in-group/out-group affinities: i.e., people want to be part of the in-group that adheres to community mores.

Public trust, understanding, and consequent willingness to comply similarly relies upon consistency. With multiple conflicting entities and regulations that do not align, this becomes difficult. In the best-case scenarios, airport operators view COVID-19 restrictions through the experience of the passenger, making it easy and even preferable to comply with proper safety practices. Signage, readily available hand sanitizing stations, and customer friendly options, such as contactless check-in, security, and baggage drop-off, make it easy and comfortable to follow the guidelines.

Airports have also found success in affording passengers easy opportunities to make risk-mitigating choices. Recognizing the following are activities airport operators can influence but do not typically control, they have:

- increased the numbers of hand sanitizing stations to improve access;
- restructured queueing at high-traffic areas, including at security checkpoints, to improve opportunities for physical distancing;
- staggered deplaning, baggage carousel use, and plane departures, when possible, to facilitate physical distancing; and
- deployed contactless technologies to help reduce disease transmission by fomites.

Modifying these physical features encourages compliance by making it convenient to maintain distance, wear face masks, and exercise proper hand hygiene. It creates the mindset that the airport is working with the passenger to shape behaviors that are easy, convenient, intuitive, and preferable to follow. As passenger volumes increase, it will become impractical or difficult to retain physical distancing between travelers. As such, alternative or supplementary layered risk mitigating interventions will become necessary.

2.5.3 Recommendations for Improving Behavioral Compliance

The social science principles and social motivators highlighted here (see also Appendix C) in this section inform the process of achieving public health safety behavior compliance. These can be incorporated in airport messaging, policy development, and creation of protocols to frame proper behaviors to reduce COVID-19. They include:

- Establishing an encompassing in-group and a sense of shared identity (Van Bavel et al., 2020). Being part of the aviation in-group provides a shared sense of identity and purpose, as in, “Here in the aviation sector, we stay safe and we stay together.” Alternatively, “We are an airport that cares about your health.”
- Setting a standard that establishes a social norm. For example, mask requirements and other mandatory public health measures can be expected behaviors.
- Leveraging principles of social approval, it is possible to promote norm adherence by encouraging acknowledging, and complementing compliant behavior (Van Bavel et al., 2020). This will not work for everyone, as every system has its outliers. Incentivizing and noting compliant behavior is a far more pleasant way to achieve it than doing so with punitive enforcement or scare tactics.
- Communications should highlight 1) advantages to the passenger; 2) the merits of protecting others; 3) the positive values reflected in compliance; 4) conformity with science and social norms; 5) gaining the approval of others; and 6) regulations that require and enforce compliance (Ben-Elia & Avineri, 2015; Schultz et al., 2007).
- Consistent messaging about formal rules (Borry et al., 2018) and reminder messaging (Dale & Strauss, 2009) can improve adherence to prescribed behavior. Therefore, using all communication channels and creating campaigns that appeal to different motives and incentives that shape public behavior are recommended. Simply, persuade by encouraging pro-social behavior and thanking people for being part of the solution. Personalized social pressure enhances compliance (see Rimer & Kreuter, 2006; Van Kleef et al., 2015).

Make it easy to comply. Extensive research into the role of built environments in facilitating health-promoting behaviors (e.g., Wilkie et al., 2018) supports the efficacy of enabling desired behavior by appropriately configuring the environment. Structure the airport experience so that at every turn, compliance with public health behavior is the best, if not the only option. It is important to build on existing knowledge from everyday life and if expected behavior at the airport is different to explain why. Improving compliance behavior includes at least three aspects, namely education, control and enforcement. Being creative and innovative can help make public health safety easy and even automatic.

Be ready to address resistance and speak to misinformation with empathy and understanding. People arrive at airports with a range of pandemic-related anger, myth, crisis fatigue, and loss. Be ready for it. Show understanding. An airport is not a social service agency, though it is all about people, and the tremendous difficulty and pain everyone now endures through this crisis. Ongoing training and updates for the workforce remain important, with a requirement to follow public health protocols as a condition of employment.

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3.0 SUMMARY OF AIRPORT PRACTICES

To learn how airports are responding to the COVID-19 pandemic, Aviation Public Health Initiative (APHI) researchers conducted a detailed qualitative study between October and December 2020 (see section 3.1). The team surveyed 23 U.S. airports and two non-U.S. airports, interviewed managers of six U.S. airports, as well as leaders in airport associations and organizations associated with airport operations. The aim was to learn more about current airport practices related to operationalizing the layered approach to SARS-CoV-2 transmission risk mitigation and gain insights into current practices and potential future innovations.

The sample of U.S. airports reflects different areas of the country, airport sizes, and international and domestic facilities. While there are some common features of airports, such as security checkpoints, they vary significantly in governance, culture, infrastructure, and passenger volume. Despite these differences, the surveys and interviews provide a substantive basis upon which to assess airport pandemic practices and to provide recommendations relevant to reducing the risks of SARS-CoV-2 transmission. The team also interviewed representatives of the Transportation Security Administration (TSA), U.S. Customs and Border Protection (CBP), associations representing the airport industry, and specialists in virus testing, ventilation systems, and indoor chemistry related to cleaning and disinfection. The data in this chapter provides an account of airport practices during the period under review; it was also used to inform content in other chapters and help frame the report's recommendations.

Airports in the survey employ a layering of risk mitigation strategies to reduce SARS-CoV-2 transmission for passengers, employees, concessionaires, contractors, and visitors. Current practices target activities that address known routes of SARS-CoV-2 transmission and include enhanced cleaning and disinfection regimens, upgrades to ventilation and air handling, means to encourage physical distancing (e.g., floor decals, barriers), promoting compliance with wearing face coverings/masks and use of technology to support contactless procedures in certain circumstances. Collectively, these efforts play an important role in providing layers of protection and risk mitigation to reduce transmission of the virus and help restore traveler confidence. The layered approach affords a level of 'redundancy' so that when some practices are not possible (e.g., maintaining physical distancing of 6-feet/1.83 meters), the proper wearing of face masks and enhanced operation of ventilation systems might still usefully mitigate risks of transmission..

As with every public facility, airport operators have responsibilities to ensure the health and safety of the public who traverse their facility. Under Federal law in the U.S., airport operators that accept federal assistance can use airport revenues only for airport-related purposes; the Coronavirus Aid, Relief, and Economic Security (CARES) Act grants were included in this restriction. Under the extraordinary circumstances of the public health emergency of COVID-19, the Federal Aviation Administration (FAA) issued updated guidance on December 22, 2020

(FAA, 2020) advising that some activities an airport may undertake to minimize the spread of SARS-CoV-2 may be legitimate capital or operating costs of the airport (FAA, 2020). For example, they consider "the testing and health screening of airport employees to be a legitimate operating cost of an airport to sustain the airport's workforce, upon which the continuity of airport operations depends. Additionally, airport operating costs may also include the costs of enhanced cleaning of the terminal and other areas of airport property to minimize transmission of COVID-19. These operating costs may include the purchase of incidentals and supplies to accomplish these purposes, such as screening and testing equipment, masks (which can include cloth face covers), personal protective equipment (PPE), and products for cleaning, disinfection, and hand hygiene. In contrast, the use of airport employees for public health screening is generally not considered a proper use of airport revenue." The FAA also advised, "Airports are permitted to allocate terminal or office space for testing and health screening activities and the related storage of medical equipment and supplies." (FAA, 2020). They also now permit use of airport revenue to cover the costs of health screening activities for passengers and people entering sterile areas. The Runway to Recovery, United States Framework for Airlines and Airports to Mitigate the Public Health Risk of Coronavirus, provides the U.S. Government's guidance to airports and airlines for implementing measures to mitigate the public health risks associated with COVID-19, prepare for an increase in travel volume, and ensure that aviation safety and security are not compromised (U.S. Departments of Transportation, Homeland Security, and Health and Human Services (2020)). Importantly, they advise a "multi-layered risk mitigation approach" as described in this Curb-to-Curb report.

3.1 SURVEY METHODS AND DATA ANALYSIS

To explore risk mitigation strategies for SARS-CoV-2 transmission during the 'Curb-to-Curb' travel journey, the Harvard T.H. Chan School of Public Health APHI Science and Technology (S&T) Team surveyed a selection of U.S. and international airports. The team's selection was informed by advice from airline and airport operators, aircraft and equipment manufacturers and associations representing aviation sector entities, with the final selection made by the S&T team to cover a range of different types of airports to constitute a representative sample (see Table 3.1). The S&T team designed a comprehensive survey instrument that included the following ten sections (see Appendix D):

1. Overview of the Responsibilities of Airport Operations for Risk Mitigation of COVID-19
2. Face-Coverings, Masks, and Shields
3. Cleaning and Disinfecting to Reduce Transmission by Contact with Surfaces
4. Health Screening of Airport Employees
5. Health Screening of Airport Passengers
6. Health Screening of Airport Visitors, Public (dropping off/picking up) and Contractors
7. New Technologies
8. Ventilation and Air Handling

9. Physical Distancing
10. Intra-Airport Transit

During October 2020, a letter of invitation (Appendix E) was distributed to 26 U.S. airports and five airports outside the U.S., along with an accompanying questionnaire (Appendix D). Completed questionnaires were received from 23 U.S. airports and two outside the U.S. up to December 21, 2020, a completion rate of 88.5% with respect to the U.S. airports. Most of the participating airports also submitted supplementary materials that included comprehensive 'COVID Playbooks,' with additional preparedness, recovery and action plans, and images of risk mitigation actions in situ. The S&T Team reviewed a total of 689-pages of completed questionnaires, 647-pages of supplementary materials, and five full playbooks. The team also examined additional documentation sourced from the websites of airports, federal authorities and industry groups. From the U.S. airports, six were selected for interviews. The characteristics of the airports interviewed are given in Table 3.1. Interviews of 60-minute duration were conducted between November 20 and December 18, 2020; interviews were recorded and contemporaneous notes taken. To foster the frank sharing of information, the research was conducted under a Non-disclosure Agreement, with confidentiality as to the participants assured. Accordingly, airports included in the study are not identified, other than by separate agreement.

Table 3.1 Characteristics of U.S. Airports included in the Study

Governance	City/County/State Government N=12 (4)	Port Authority N=2	Airport Authority N=7 (1)	Private Operator N=2 (1)
Primary Traffic and Source	Domestic N=15 (3)	International N=8 (3)	Connecting N=7 (2)	Originating N=16 (4)
Region	US South N=5 (1)	US Northeast N=6 (2)	US Mid-West N=4 (1)	US West N=8 (2)
Hub Size	Large N=14 (4)	Medium N=3	Small N=6 (2)	
Other	Airside buses, trains, other N=8 (2)	Innovator N=10 (3)		

N Number of airports with the characteristic concerned that submitted a questionnaire and were included in the study; figure in parentheses "( )" relates to number of airports with that characteristic that were selected for interview.
Hub Size As defined by the Federal Aviation Administration's National Plan for Integrated Airport Systems (FAA, 2020a)
Innovator Defined as an airport piloting or adopting new technologies, such as contactless processing, sensors, and cleaning automation.

Data from the questionnaires was reviewed in detail and arranged thematically, with practices reported by the airports summarized and common activities and areas of interest highlighted (see Appendix F). Interviews undertaken by the S&T Team enabled a deeper dive into key areas, with particular attention paid to governance as it relates to crisis leadership, cleaning and disinfection, ventilation measures, and innovation. Questionnaires and interviews also sought to identify any areas of concern, with interviews probing further on plans for post-COVID-19 recovery. This section further describes some practices that may be of value if implemented across the airport sector. Practices not fully informed by science, or considered a possible risk, are called out for additional review.

3.2 RESULTS AND DISCUSSION

The APHI S&T Team finds that airports in the study are making concerted efforts to reduce the risk of SARS-CoV-2 transmission in the airport environment as it relates to the Curb-to-Curb traveler experience.

The results of the survey and interviews illustrate the range of intervention measures airports have introduced to mitigate risk of SARS-CoV-2 transmission. Typically, they are in accordance with what is known about how the virus spreads, with efforts targeted to interfere with known routes of SARS-CoV-2 transmission (see Chapter 2). For example, one airport notes it has installed over 2-miles of plexiglass barriers, added over 5,000 floor decals and 2,500 signs, with 500 hand sanitizer stations; it also makes relevant announcements in two languages every 10 to 15-minutes, offers enhanced cleaning and has reviewed its ventilation and air handling systems**.** **Innovation in the sector is strong**, as seen in the adoption of contactless technologies, sensors, and automation. From the use of mobile phone applications (apps) to order food and reserve a timed slot in security checkpoint lines, to the use of sensors to monitor passenger flows and carbon dioxide (CO_2) levels (for ventilation control) and robot cleaning and disinfection, airports are innovating. Airports are also sharing lessons learned through membership associations and industry bodies. The industry is investing in education and training. For example, one airport program focuses on healthy habits education. Most are also collaborating with public health bodies and other airport groups, locally, nationally and internationally. There was no material difference in the strategies shared through the survey instrument by the two non-U.S. airports compared with the 23 U.S. airports, noting the sample size for the former was very small.

While information developed for addressing the pandemic has been helpful to airports, the absence of federal guidance early in the crisis and variable state and local practices in the U.S., meant that each airport has largely been responsible for determining its own approach to COVID-19 response protocols. In addition, each airport team is working to keep up with the quickly evolving science about SARS-CoV-2 and COVID-19 and contextualizing these findings to their unique airport environment. They are also spending time examining and piloting a wide variety of potential solutions and innovations offered by vendors—some of which have yet to demonstrate science-based evidence of efficacy. **Among the airports surveyed and interviewed, most commented on a desire to see greater consistency across the industry, noting this would help support passenger confidence and enable targeted financial investments in support of faster industry-wide recovery.** Given most passengers will experience two or more airports in their Curb-to-Curb journey, consistency will support confidence as well as compliance. Airports were all interested in being able to provide passengers with multiple options to protect themselves, and the layered approach to risk mitigation fits well with this overall objective.

The following sections review the **questionnaire** topics (A – J) in turn, together with key learnings from the **interviews**, and highlight key practices and any topics of ongoing concern. Where the term 'airport(s)' is used, this relates to those airports included in the study. Given the variety of U.S. airports surveyed, some inferences apply generally to practices across the airport industry, both domestic and international.

3.2.1 Overview of the Responsibilities of Airport Operations for Risk Mitigation of COVID-19 (Questionnaire, section A)

The airports surveyed were all active in risk mitigation applied to SARS-CoV-2 transmission in their facilities, incorporating health and safety practices into the staff and traveler experience. **Airport mitigation strategies demonstrated a substantive grasp of SARS-CoV-2 transmission routes, with interventions designed to reduce spread by all known routes.**

Given the high risk of SARS-CoV-2 spread by aerosol and droplets, the leading mitigation strategy was the use of **face coverings/masks** (see Figure 3.1). Face masks are typically mandated for all airport employees. In most areas of the U.S., they are also mandated for all persons on airport property including travelers, concessionaires, contractors and visitors. Face coverings/masks were offered free of charge in most airports, with some also providing masks for purchase through vending machines and stores. **Compliance** was monitored primarily by staff, who encouraged others including passengers to wear their masks properly. In some airports, staff formally adopted a travel well 'ambassador' or 'guest champion' role, in others, security staff and on-site police officers promoted compliance. One airport established a 24/7 hotline for COVID-19-related issues, should a staff member have concerns around compliance.

Figure 3.1 Examples of Airport Signage Relating to Face Coverings/Mask Wearing

In support of efforts to reduce the risk of viral spread via inhalation, most airports had installed clear acrylic sheets or plexiglass **barriers and screens** at locations where employees and passengers interact face-to-face; this seems entirely appropriate. However, the S&T Team learned that plexiglass screens were also being considered and/or used as barriers to support physical separation while queuing in certain locations. Given the extensive modelling studies undertaken by the S&T team **caution in the application of barriers in queue situations is advised** as this may create 'canyons' that could interfere with effective ventilation (see Chapter 7 for full details of the types of barriers, layout, and risk modelling). This has the potential to both exacerbate the risk of airborne routes of transmission, and to create additional opportunity for risk of fomite transmission.

Physical distancing is promoted actively at all the airports surveyed using digital and physical signage, floor decals are used to indicate 'safe' spacing, (see Figure 3.2) with regular public announcements made to support compliance.

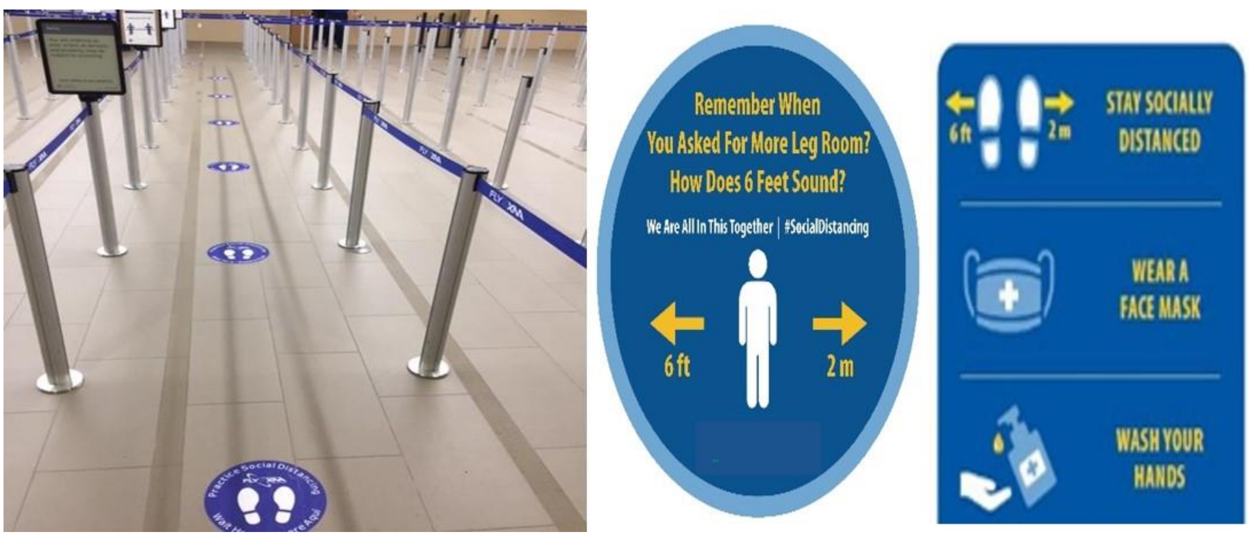

Figure 3.2 Examples of Airport Physical Distancing

A range of **contactless technologies** was already in use before the COVID-19 pandemic, with the crisis providing an impetus for further investment and adoption of digital technologies. One airport mentioned it would be possible to complete the Curb-to-Curb journey almost entirely contactless.

Regular, typically daily, **health attestation** was in place for employees at most airports, with symptom screening for COVID-19 (see Chapter 6) and temperature checks. Some airports extended this approach to all concessionaires and contractors; others also included visitors. Several airports altered **staff work patterns** by staggering shifts and platooning staff to help reduce potential cross contamination and enable more rapid contact tracing. While **contact tracing** is the responsibility of local public health authorities, three airports mentioned it as part of their layered approach to risk mitigation.

With respect to possible transmission via fomites, all airports have deployed **hand sanitizer** stations and have enhanced considerably their **cleaning and disinfection** regimens. These include innovations, such as ultraviolet (UV) disinfection of escalator handrails (see Figure 3.3).

Figure 3.3 Example of UV-Light Disinfection of Escalator Handrail

In support of efforts to demonstrate best practices, some airports sought external **accreditation of their cleaning and disinfection** protocols to offer a level of independent validation. Some turned to certification programs open to the aviation sector only, others chose a program recognized outside the sector, and some followed both routes (see section 3.2.3) . Those airports that have secured accreditation, or were in the process of doing so, commented that this can help with training of employees, awareness, and the promotion of public health in the airport environment. It could also help restore public confidence in the airport experience, with airports in the study recognizing the additional public relations benefits of highly visible cleaning undertaken in public facing settings.

Within the airports, managers have mounted robust information and awareness strategies. COVID-19 crisis planning responsibilities are coordinated through consistent and intentional **communication** directed toward airport employees and wider airport stakeholder groups. Most airports used daily/weekly team meetings, often supported by task groups. Senior leadership was visible, with efforts to drive engagement throughout the airport community. Crisis leadership demanded the ability to navigate high-degrees of uncertainty in a challenging financial situation. Many airport preparedness, recovery, and action teams developed comprehensive playbooks on managing the pandemic emergency.

In one interview, an airport described the creation of a cross-functional Executive Readiness Task Group that included all airport stakeholders in developing a Pandemic Preparedness Plan. This group developed a training and education program for airport employees and concessionaires to support consistency of messaging and practices. It encouraged people to share ideas and feedback, a process known to deepen employee engagement through workplace psychological safety (Edmondson, 2019) and to increase productivity (Baldoni, 2013). Another airport interviewed by the S&T team created a COVID-19 Action Plan that included all tenants and established a Social Responsibility Group that worked with its city Safety, Health and Environment team. One airport's strategy for developing ideas focused on what can be done now and in the future, with staff workshops set up to gather project ideas. Another set up a 'well building' task force with regional health, education, technology and non-profit organizations as members. A 'Fly Healthy' agenda enabled several airports to convene people around a shared purpose, creating and enabling culture change (Goleman, 2013; Gast et al., 2020).

Among the concerns expressed by airports, the most frequent was the absence of a consistent and clear set of protocols across the industry and between local and destination/origin jurisdictions, with each airport largely responsible for charting its own course in the absence of clear and consistent federal requirements. Most airports were concerned about maintaining physical distancing once passenger numbers return to pre-COVID-19 levels. Face coverings/masks compliance was typically high, with people largely responsive to reminders from airport staff. However, there was concern that pandemic 'fatigue' may make this more difficult going forward.

3.2.2 Face-coverings, Masks and Shields (Questionnaire, section B)

Face-coverings/masks are mandated at almost all airports for all people; typically, young children were exempt, in line with Centers for Disease Control and Prevention (CDC) COVID-19 guidelines. The presidential executive order issued on January 21, 2021 mandates that "masks to be worn in compliance with CDC guidelines in or on: airports, commercial aircraft…" and a number of other public conveyance locales (The White House, 2021). On January 31, 2021 the TSA announced it would implement the executive order regarding face masks at airport security checkpoints throughout the U.S. domestic network of airports for passengers over 2-years old and crewmembers, coming into effect February 2, 2021 and effective through to May 11, 2021; it also covers the commercial and public transportation systems (The White House, 2021a; TSA. 2021)

Airports in the survey reported compliance with wearing face coverings/masks to be substantial, with airports making significant efforts to support this public health practice. The major concern expressed at the time of the survey was variability of mask wearing regulations—varying between state (the majority), county, city, and airport orders. This made consistent messaging difficult and potentially confusing for passengers. The aforementioned executive order should help address this concern. Most airports support compliance with friendly reminders by staff. Only one example of enforcement by Police was given, with issuance of fines for non-compliance. Typically, however, airports have few if any escalation procedures with many having made the decision not to implement stringent enforcement measures. Only the airlines are able to deny travel for non-compliance with airline facial covering policies. The implementation of the executive order by TSA again should help support compliance. The other issue was ensuring procurement of enough safety, sanitation and personal and protective equipment (PPE) supplies, a national problem for many facilities, including hospitals.

3.2.3 Cleaning and Disinfection Practices (Questionnaire, section C)

Airports are investing significant resources in enhanced cleaning and disinfection using government-approved disinfectants (in the U.S., these are the Environmental Protection Agency [EPA]-approved N-list disinfectants; see section 4.1, Chapter 4) for cleaning surfaces. Standard operating procedures (SOPs), manuals and checklists are in place, with many airports using external contracted services. One airport interviewed by the team had taken over responsibility for cleaning in concessionaires' spaces to maintain consistency of approach. Some of the airports surveyed had secured, or were in the process of applying for, accreditation by the Airports Council International (ACI, 2020) or through the American Association of Airport Executives (AAAE) partnership with the Global Biorisk Advisory Council (GBAC, 2020) STAR program.

- The **ACI Airport Health Accreditation Program** is a voluntary, industry-specific self-assessment that seeks to obtain a full picture of airport practices relevant to airport cleaning and disinfection, physical distancing, signage, communication and facilities based on International Civil Aviation Organization (ICAO) CART topics (CART, 2020). The program relies upon an airport completing a self-assessment, followed by an online ACI validation interview with key airport personnel. Then, either recommendations are made for improvement or accreditation is awarded for the next 12-months. Ongoing accreditation relies on continuous improvement and regular evidence-based self-assessment submissions to ACI. As of January 19, 2021, 59 airports in North America (U.S. and Canada) have committed to participate in the ACI Airport Health Accreditation Program and 45 have already been accredited.

- **GBAC** is a division of ISSA (ISSA, 2020), a worldwide cleaning industry association, that partnered with AAAE to deploy its programs at U.S. airports. The overall program is not specific to the airport sector, focusing on helping organizations and businesses prepare for, respond to, and recovery from biological threats and biohazard situations. The **GBAC STAR™** is the cleaning industry's only outbreak prevention, response and recovery accreditation for facilities. This accreditation means that a facility has established and is maintaining a cleaning, disinfection, and infectious disease prevention program to minimize risks associated with infectious agents like SARS-CoV-2. A facility prepares its submission documentation in line with the GBAC handbook; the GBAC Council reviews this for compliance and, if successful, grants accreditation subject to annual review. AAAE and its members collaborated with the GBAC Scientific Advisory Board to develop a GBAC Airports Guidance Handbook that advises airport employees on best practices to combat biohazards and infectious disease. As of January 15, 2021, 54 airports of all sizes are pursuing GBAC accreditation and 17 have already received their GBAC STAR™ and accreditation.

Several airports had invested in or were exploring innovations in cleaning and disinfections practices. In the survey, five airports mentioned they used electrostatic spraying, nine used robots for cleaning/disinfecting/self-sanitization and nine mentioned using ultra-violet (UV) radiation. Cleaning and disinfection are discussed in detail in Chapter 4.

3.2.4 Health Screening of Employees, Passengers, Visitors, Public and Contractors (Questionnaire, section D-F)

The airports surveyed in this study provided numerous examples of health screening practices. Most required daily **health attestations** by employees that included either checking for COVID-19 symptoms and/or **temperature** checks. In January 2021, requirements for international passengers inbound to the U.S. and Canada were changed with travelers asked to provide health attestations (and proof of negative molecular or antigen tests; see Chapter 5) as a condition for boarding their flights. Health attestation of passengers is typically done by airlines, although one airport mentioned using health screeners to interview passengers upon arrival at the airport. Several of the airports extended **paid sick leave** to enable employees to self-isolate. Airports relied on concessionaires and contractors to follow suit, albeit most did not check on their practices or mandate them contractually. About half of the airports surveyed employed **different screening protocols for their own employees versus other airport staff**, such as vendors, contractors, and airline personnel. This **variability** may carry some risk that could be attenuated if an all-staff protocol were in place. Temperature screening for airport employees is commonly used despite it being known to be of relatively low value in identifying positive COVID-19 cases (Menni et al., 2020; Richardson et al., 2020; see Chapter 6 for details on health screening).

Among the key concerns expressed by survey respondents and those interviewed related to tenant compliance with protocols and transmission among employees outside of work. Given most secondary transmission of COVID-19 occur in the home (see Chapter 2, section 2.4), off-site risks are a relevant concern given those infected at home could bring the virus to work.

As such, some airports have revised shift patterns and platoon staff so that it will be easier to identify contacts and enable people to self-isolate should an employee experience symptoms. Several currently offer on-site free/low fee **COVID-19 testing**, with some making this accessible to passengers and visitors/members of the public as well. About half of the airports surveyed are considering acquiring or testing new screening technologies or procedures and offering on-site testing facilities in partnership with external companies. More than half of the airports do not have on-site health medical assistance beyond emergency services. Many of the airports now discourage non-traveling visitors, so-called 'meeters and greeters', from entering the airport to reduce congregation risks unless they are accompanying vulnerable people or minors.

One airport offering on-site testing described how it had worked in concert with the CDC when a COVID-19 positive passenger was detected. Having advised the CDC, the person was quarantined at a nearby CDC-approved hotel. However, a few days later, the person tried to re-enter the airport and the TSA 'do not board' flag enabled the airport and airline to manage the situation safely. This illustrated a concern expressed by several airports—that a sick passenger may still attempt to travel by air.

3.2.5 New Technologies (Questionnaire, section G)

Prior to the pandemic, most of the airports were already investing in their digital and innovation strategy with a range of technology solutions and innovations in place. The COVID-19 crisis has served to accelerate technology adoption, such as applications (apps) and contactless technologies, including voice commands. Technologies that support remote queuing and reservation technology to support appropriate physical distancing were also being explored.

One international airport is investigating the use of data analytics to support its 'healthy airport' commitment. Autonomous cleaning technology as well as UV disinfection robots are in use or being piloted by several airports. Many airports are paying special attention to restrooms, disconnecting hand dryers and installing contactless fixtures with upper air disinfection using UV; some airports had re-introduced restroom attendants. A number of the airports surveyed are piloting the use of digital assistants with TSA, CBP and airlines all focused on digital solutions to support simplified check-in, security checkpoint, boarding and arrivals procedures. TSA's Enhanced Advanced Imaging Technology (eAIT) and Credential Authentication Technology (CAT) combined with a camera are good examples of this strategy in action.

3.2.6 Ventilation and Air Handling (Questionnaire, section H)

The Phase One Gate-to-Gate report (Harvard APHI, 2020) focused on the aircraft environment and highlighted how enhanced ventilation during deplaning and boarding can help reduce the risk of exposure to COVID-19. Turning to the Curb-to-Curb part of the journey, most of the airports in the study already had various types of air filters in their heating, ventilating and air-conditioning (HVAC) systems before the COVID-19 pandemic struck and several have upgraded the filter efficiency in their systems to those with higher Minimum Efficiency Reporting Values (MERV) in response. Many airport HVAC systems currently in operation have filters that block larger particles from entering the equipment section and deposit on the internal components of the equipment and interfere with its performance. They were not intended to filter smaller, virus size particles. Current industry recommendation with regard to COVID-19 responses is to use a MERV 13 filter, which is at least 85% efficient at capturing particles in the 1-3 µm size range. The ability to retrofit these upgraded filters into existing equipment must take the capabilities of the HVAC systems into consideration so that its overall operation is not degraded (see Chapter 7).

Generally, increasing the filter efficiency leads to an increased pressure drop that can lead to reduced airflow through the HVAC system or, the use of more energy by the fan to compensate for the increased resistance through the higher rated filters. Operators generally want to use the highest MERV rating that the equipment can accommodate without degrading performance. MERV 13 is the minimum recommended rating in an area with a significant amount of recirculated air. If installed equipment cannot accommodate the higher level of filtration then supplementary filtration may be required in some settings (see Chapter 7).

Some HVACs use air-handling units (AHUs) with UV light systems and ionization systems installed. Some airports are planning upgrades. Many of the changes made to the AHUs are driven by programming, ventilation, and filtration efficiencies for more demand-controlled ventilation and for some airports to meet the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) airflow and management recommendations aimed at reducing COVID-19 risk (ASHRAE, 2020). Some airports have installed air quality monitoring systems in their terminals. As discussed in Chapter 7, consideration of physical distancing and filtration of air will be affected by how many people the air flows past between a source and an exhaust. Increases in the delivery of dilution air or shorter air paths to the exhaust will greatly reduce the potential for transmission. Further, the use of clean outside air, where climate conditions permit, can compensate for limited filtration capability.

3.2.7 Physical Distancing (Questionnaire, section I)

All the airports surveyed reported ubiquitous use of physical and digital signage to encourage physical distancing, combined with regular public announcements. Most airports blocked or removed seats, cordoned off areas to reduce congregation (see Figure 3.4), and closed play areas and business centers. Passenger queuing for security screening was modified in several airports to ensure separation, while some are piloting remote queuing software and one-way pedestrian traffic routing. Some of the airports had dedicated ambassadors to encourage passenger physical distancing measures. Most airports used their websites, social media, radio commercials, mobile apps, and newsletters to communicate the physical distancing expectations passengers and others will encounter upon arrival at the terminal. This was supplemented by airlines, which have the capability to communicate directly with some of their passengers in advance of their arrival —an option not generally available to airports. Once passengers are inside the airport, physical distancing strategies, such as the use of digital technologies, seek to manage congestion and congregation.

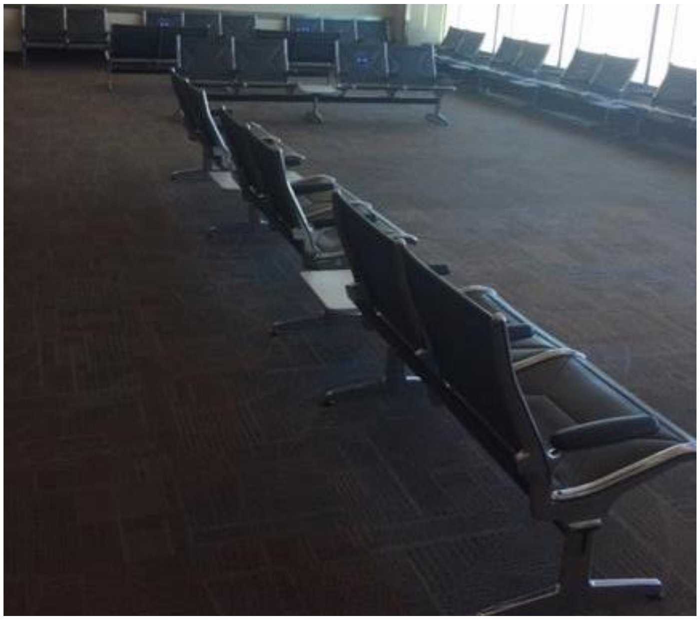

Figure 3.4 Example of Airport Seating Configured to Reduce Congregation

In some states, airport restaurants were required to close seated dining (even if properly spaced) in line with state or local rules, only allowing food pick-up and delivery. The unintended consequence of this policy resulted in increased congestion in gated and seated areas and mixing of unmasked (removed to eat or drink) with masked travelers. This is an example in which one precautionary measure could potentially exacerbate overall transmission risks. Concerned airports lobbied states to change these policies, and the science supports the importance of these considerations in risk mitigation.

Approximately half of the airports implemented additional services for arriving passengers, such as self-serve PPE stations, hand sanitizer and information on local mandates and regulations. In order to minimize congestion around baggage carrousels, some of the airports changed baggage-handling procedures to support physical distancing. Examples shared by those airports in the survey included: changing the assignment of baggage carousels to maximize physical distancing; evenly spreading luggage across multiple carousels; sharing baggage carousels across more than one carrier, and defining a pathway for retrieving luggage and exiting the area.

A significant concern expressed by the airports was future congestion in facilities once higher passenger numbers return and how physical distancing might then be supported. One suggestion includes spreading out active gates to avoid generating crowding from aggregated flights in the same concourse, although agreements about how gates are used by specific airlines could make this approach difficult to implement. Increasing airflow will be helpful but, well-designed and properly implemented local air cleaning or disinfection devices, such as germicidal ultraviolet (GUV, or UVGI —ultraviolet germicidal irradiation) may be of significant benefit in these types of settings. **The layered approach to risk mitigation is relevant here as physical distancing from 6-feet (1.83 meters) can be reduced when other mitigation strategies are optimally applied, e.g., wearing a face covering/mask, hand hygiene and improved ventilation effectiveness** (Morawska et al., 2020).

3.2.8. Intra-airport Transit (Questionnaire, section J)

About half of the airports in the study offered intra-airport transit options. Most airports use shuttle buses for transport between terminals and parking lots; some have automated people mover (APM) trains. Airports with APMs continue to operate their systems to handle transfers between terminals, adding measures to reduce risk. As it is difficult to maintain physical distancing within vehicles, most airports simply reduced the number of passengers per vehicle, increased the frequency of trips, installed signage to encourage physical distancing, added plexiglass barriers and undertook additional cleaning and disinfection. Staff were also asked not to ride the shuttles or trains at peak times. Several shuttle-servicing parking lots have been suspended as passenger volumes decreased, and most of the airports with airside bus systems have suspended the service during the pandemic to avoid busing passengers from hard stands to the terminals; further information on transit risk mitigation is given in Chapter 7.

3.3 CONCLUSIONS

The threat environment created by the COVID-19 pandemic in a multi-node environment such as an airport is challenging given the multiple routes of transmission of SARS-CoV-2 that pose a threat and the behavioral dimensions to managing the risks (see Chapter 2, Section 2.5). The adage, "If you've seen one airport, you've seen one airport." is especially apt when considering implementation of measures to address the COVID-19 situation. In addition to the variation among and within airports, different regulations and requirements imposed by state and local entities, the lack of a federal playbook and the unfolding nature of the science have put airports in the position of navigating high degrees of volatility, uncertainty, complexity and ambiguity — so-called VUCA conditions—since the pandemic struck. **Despite this variability, the airports in the study were found to have implemented significant precautions to reduce the risk of SARS-CoV-2 transmission and demonstrated substantive understanding of the science and strategies to mitigate disease spread.** While the airports in the study are a small sample, their actions provide a reasonable foundation for further development, innovation, and implementation of industry-wide public health measures.

Despite the complex conditions in which they are operating, airports in this study made timely science-based decisions to manage the COVID-19 threat by adopting a layered approach to risk mitigation. Typically, interventions were in accord with what is known about the routes of transmission of SARS-CoV-2, with face coverings/masks, hand hygiene, physical distancing, ventilation and cleaning and disinfection at the heart of most mitigation strategies. Human factors are also important in securing compliance. Innovation in the sector abounds, with an acceleration of digital solutions being deployed or piloted. Learning is shared across the sector, with professional and industry associations playing an important role. Acceleration of best practices together with securing evidence of efficacy as it relates to innovative practices would be expected to afford greater consistency across the industry. Following the science will also support public confidence.

COVID-19 has likely changed the aviation industry forever. While passenger numbers are beginning to recover, many of the containment and risk mitigation strategies now in place are predicted by the S&T Team to continue once the crisis has subsided and vaccination programs are well advanced. However, some practices will likely be able to return to pre-pandemic practices, such as the enhanced cleaning and disinfection, since transmission via fomites has been found to be a low probability route of transmission (Goldman, 2020; Meyerowitz et al., 2020).

The public perception is that anyone working in an airport is under the management of that airport; travelers do not distinguish among employees, concessionaires or contractors. At some airports, leaseholders and concessionaires took varying approaches to cleaning and disinfection and employee requirements. The S&T team consider this a potential cause for concern. Many of the airports in the survey had set up shared leadership groups to promote synchronization. **Consistency of practices across airport employees, tenants, contractors, and visitors will support peer-to-peer compliance as well as make it easier for passengers to understand what is expected of them. Consistency across U.S. airports will likewise support public confidence and compliance.**

Overall, the airports in the study are implementing comprehensive strategies to mitigate the impact of COVID-19 on their employees, passengers and the wider airport community. Most have adopted a layered risk mitigation approach in line with the science of SARS-CoV-2 and known routes of transmission. Good and best practices are present across the industry and greater harmonization of practices will support focused investment in risk mitigation measures and preclude those that offer little benefit. Once basic preventative measures had been implemented, most airports pivoted to focus on building confidence, promoting the passenger experience and strategic investment in value-add practices to further mitigate risk. Most airports considered that national pandemic standards and/or advice for the sector would help inform their efforts as an industry. Emergent recommendations informed by the study are given in the Executive Summary.

The S&T Team is very grateful to the airports that agreed to participate in the study, and for the time they invested in completing the comprehensive questionnaire and participating in interviews. Airports shared their materials, practices, ideas and concerns freely with the S&T team. Given the other pressing demands on their time, this was extraordinarily generous. Their participation provided extremely valuable insights that informed this research, its findings and recommendations.

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4.0 NON-PHARMACEUTICAL INTERVENTIONS (NPI) AND THE LAYERED APPROACH FOR RISK MITIGATION AT AIRPORTS

As outlined in Chapter 2, the layered approach to risk mitigation through the application of multiple non-pharmaceutical interventions (NPIs) is especially suited to adoption in airport settings. This is because of the complexity of airport terminals and their heterogeneous nature in terms of architecture, layouts, passenger numbers, culture and governance. As such, the airport environment is much more complex when it comes to studying SARS-CoV-2 transmission risks and mitigation efforts. NPIs as they apply to the 'Curb-to-Curb' journey (see Figure 2.2, Chapter 2) fall into three general categories, namely: personal, community and environmental. These can be combined to provide a **layered NPI approach** that seeks to capture the additive or synergistic risk mitigation effects of each intervention.

Personal measures include actions such as handwashing and wearing a mask, and are influenced by behavior and culture (see section 2.5, Chapter 2). Community measures include policies and strategies, and would include actions taken by airport operators to raise awareness about how SARS-CoV-2 spreads, and tackle known routes of transmission (see Chapter 2). Environmental measures include means to limit viral exposure and contamination, such as cleaning and disinfection (see section 4.1, Chapter 4) and ventilation (see Chapter 7).

This chapter explores hygiene (disinfection and cleaning), including means to determine its effectiveness, and the adoption of contactless technologies to reduce physical contact with surfaces and support physical distancing. Given modeling and measurement studies consistently support the assertion that applying multiple NPI across the different levels of control can be highly effective at reducing the spread of SARS-CoV-2 (Cowling et al., 2020), a critical evaluation of the combination of various risk mitigation strategies in various 'target' airport settings was undertaken using a Monte Carlo analysis (see section 4.3 and Appendix G). This compared typical NPI applied in an airport setting and calculated risk mitigation across three scenarios. As more information becomes available with respect to the spread of SARS-CoV-2, the effectiveness of various control measures will continue to be quantified.

4.1 DISINFECTION TECHNOLOGIES AND CLEANING PRACTICES AT AIRPORTS

Disinfection refers to the deactivation or killing of infectious agents, while **cleaning** relates to the process of removing visible dirt and particles. If appropriate products and procedures are employed, disinfection may occur at the same time as cleaning (WHO, 2009).

In order to understand how long SARS-CoV-2 can remain infectious, aerosols and virus-containing droplets on surfaces have been studied to assess risk and determine the efficacy of various cleaning and disinfection protocols. van Doremalen et al. (2020) conducted stability studies with SARS-CoV-2 in the laboratory. Aerosol studies at 65% relative humidity (RH) and 21-23°C, and surface viability at 40% RH and 21-23°C suggest that SARS-CoV-2 *remains* infectious for several hours in the air, and several hours to several days on surfaces depending on the type of surface material (van Dormalen et al., 2020). Similar aerosol studies conducted at RH levels ranging from 40 to 88% generally agree with these results (Smither et al., 2020). However, these studies were conducted in laboratory environments with ideal and/or known conditions (i.e., air temperature, humidity). It is known that temperature, humidity, and ultraviolet (UV) light (i.e., sunlight) affect virus survival. In one study using simulated sunlight, the virus was inactivated on surfaces within 20 minutes (Ratnesar-Shumate et al., 2020). Further, findings suggest that environmental contamination leading to SARS-CoV-2 transmission via fomites is unlikely to occur in real-life conditions, such as health-care settings, provided that standard cleaning procedures and precautions are enforced (Colaneri et al., 2020; Mondelli et al., 2020). These data would support the position that the chance of transmission through inanimate surfaces is less frequent than currently thought. The science community and the aviation community need to continue to study this topic in operational environments to resolve this issue.

The latest guidance from the CDC (CDC, 2020a) and the WHO (WHO, 2020a) state that **surfaces are *not* thought to be a significant route of SARS-CoV-2 transmission**. Inhalation of droplets and aerosols or direct deposits from droplets onto the eyes, face, or body are more important for transmission when people are in close proximity (CDC, 2020a). Research suggests that **contact with contaminated surfaces or objects, termed fomites, accounts for less than 10% of the overall risk of transmission of SARS-CoV-2** in certain high-risk settings such as healthcare facilities (Jones, 2020). However, the Jones simulation and other research indicate that fomites may still have a role in disease transmission, even if not a primary one (Jones, 2020; Karia et al., 2020; Wei et al., 2020; Xiao et al., 2020). Disinfection and cleaning therefore remain relevant to efforts to mitigate SARS-CoV-2 via direct contact with infected fomites and subsequent transfer to the eyes, nose, or mouth until more research is completed.

Disinfection of surfaces in airport terminal buildings should remove any virus or pathogens deposited onto surfaces by an infected person (Wei et al., 2020). Airports have developed enhanced disinfection and cleaning regimens during the COVID-19 health emergency. In the U.S., they use physical surface disinfection with fabrics, mops, or brushes using disinfectants included in the Environmental Protection Agency (EPA) List N: Disinfectants for Use Against SARS-CoV-2; the EPA N-list disinfectants kill 99.9% of SARS-CoV-2 (EPA, 2021). Some also use enhanced surface disinfection methods and technologies like electrostatic spraying, germicidal ultraviolet (GUV) systems, and/or antimicrobial coatings (see sections 4.1.1 and 4.1.3). Before the COVID-19 pandemic, cleaning was routine and disinfection undertaken more intermittently (WHO, 2009). However, as people infected with SARS-CoV-2 may be pre-symptomatic for several days (He et al., 2020) and 40 to 45% of SARS-CoV-2 infections are considered asymptomatic (Oran & Topol, 2020) they are potentially spreading virus without being aware (Ferretti et al., 2020; Prather et al., 2020, Sommerstein et al., 2020). **As such, and as a continued precaution, disinfection and cleaning should be frequent and comprehensive.**

Most organizations have long complied with standard international training, cleaning and disinfecting guidance (WHO, 2009) and are following enhanced disinfection principles relevant to the pandemic, such as:

- Planning of cleaning and disinfection activities according to the specific setting (e.g., passenger gates, cargo areas, food courts etc.), size of the area, and time available.
- Focusing on high-touch surfaces that require extra attention.
- Following standard protocols on method of disinfection for every surface (e.g., escalator handrails, arm rests in waiting areas at gates, food court tables).
- Training staff on how to wear and use relevant personal protective equipment (PPE; e.g., gloves, face masks, etc.) to prevent occupational hazard and risks including exposure to cleaning agents or methods (e.g., UV light).
- Adhering to regular schedules to systematically disinfect and clean areas daily, at peak-times, at scheduled times, or in-between flights.
- Using disinfectants approved by regulatory bodies.
- Adjusting routine cleaning programs if a public health risk is detected and/or if advised to do so by public health authorities.

Airport operators may have their janitorial team on staff or supplied through a company contracted by them. **Some airports have or are in the process of obtaining voluntary accreditation or certification of their cleaning and disinfection practices**, for example, from the American Association of Airport Executives (AAAE) partnership with the Global Biorisk Advisory Council (GBAC) or from the Airports Council International (ACI) (see section 3.2.3, Chapter 3).

- GBAC offers standard science-based frameworks, with procedures and checklists for compliance of disinfection in different areas of the airport such as bathrooms, food courts, security screening, break rooms, etc. (GBAC, 2020); it is sector agnostic.

- ACI offers two accreditation schemes for cleaning and disinfection specific to the airport environment. The ACI Airport Health Accreditation program assesses how aligned an airport's health measures are with the ACI Aviation Business Restart and Recovery guidelines and the International Civil Aviation Organization (ICAO) Council Aviation Restart Task Force. The ACI Airport Health Measures Audit Program, developed with

Bureau Veritas and based on the SafeGuard standards, offers an onsite audit covering all airport processes, using an airport-specific checklist (ACI, 2020).

Overall, there is a low probability of being infected via fomites in an airport, especially since transmission of SARS-CoV-2 is mostly airborne (WHO, 2020a). Disinfection and cleaning practices at airports are substantial. High-touch surfaces are cleaned frequently, with effective disinfecting agents approved by governmental agencies and reinforced by industry oversight bodies.

As of December 2020, over 2.8 billion passengers have been carried by airlines operating scheduled flights with no reported COVID-19 outbreaks at airports (ICAO, 2020). The effectiveness and the visibility of enhanced cleaning and disinfection measures has done much to ensure public confidence in spending time in the airport environment.

4.1.1 Electrostatic Spraying of Active Ingredients

Some airports use portable electrostatic sprayers to apply EPA-approved disinfectants to surfaces (including those that are hard-to-reach). The EPA recently approved several disinfectants for application via this method with more under review (EPA, 2021), albeit the overall effectiveness of such spraying applications for use against SARS-CoV-2 has not been fully assessed. As the chemicals pass through the sprayer nozzle, positively charged disinfectant droplets are generated that can attach to negatively charged surfaces. Disinfecting agents are applied wet and left to dry, enabling the required contact time to disinfect surfaces (APHC, 2020). When an electrostatic sprayer system is used, a cleaning agent with neutral or close to neutral pH needs to be used; products for safe use on electronics are approved by SAE International standards (SAE, 2015). Quaternary ammonium chloride is generally used because it is naturally positively charged and remains chemically stable throughout the application process. Other cleaning agents used include hydrogen-peroxide, hypochlorous acid, and bleach-based cleaning products. Preferred products include those with ‘No Wipe’ usages, which means that little or no residue remains after the manufacturer’s recommended contact time (APHC, 2020). The effectiveness of cleaning and disinfection practices can be assessed using a technique to detect Adenosine Triphosphate (ATP) as a biological indicator (Sifuentes et. al., 2016; Sanna et al., 2018; see section 4.1.2).

4.1.2 ATP Testing to Check the Effectiveness of Disinfection Practices

The implementation of disinfection practices can help reduce the spread of viral illnesses in the workplace. Traditional methods for evaluating the effectiveness of different regimens, such as standard direct microbiological tests that collect microorganisms and culture them in a laboratory, are labor intensive, time-consuming and likely not to be cost-effective for use in large areas such as airport terminals (Turner et al., 2010; Sanna et al., 2018). As such, rapid methods for screening of relative biological loads on surfaces can be useful in evaluating the efficacy of mitigation efforts. A rapid assay to test for the presence of microbiological contamination and verify large-scale disinfection of surfaces is the ATP test (Sifuentes et al., 2016). This test can be used as a rapid screening method to evaluate workplace hygiene interventions in reducing the potential for viral spread. Commercially available ATP test kits use a luminometer to check for the bioluminescence of luciferin (a light emitting organic compound) when exposed to ATP (see Figure 4.1). While ATP testing cannot confirm or refute the presence of specific microbes, it is useful in checking the effectiveness of disinfection regimen aimed at preventing viral spread in the workplace.

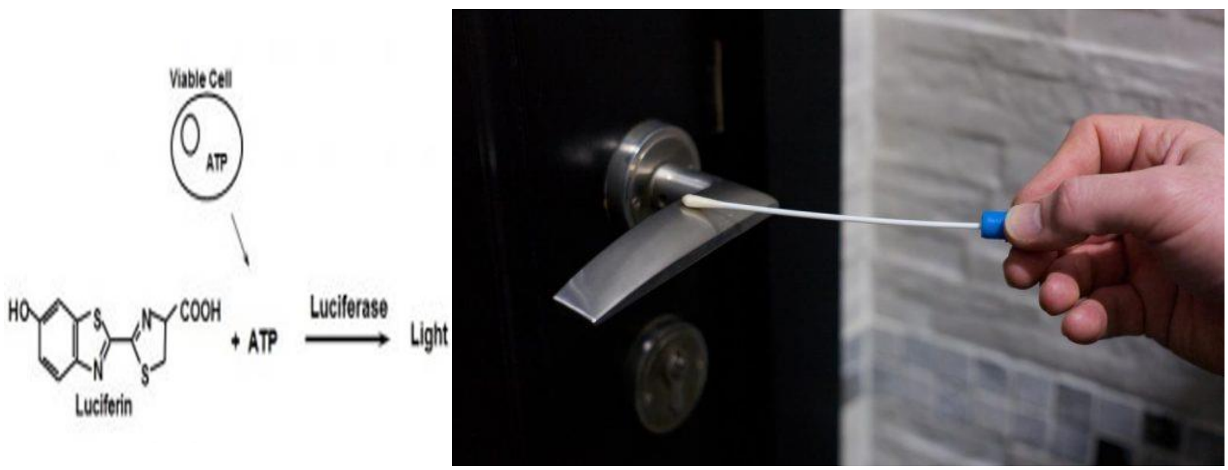

Figure 4.1 The ATP reaction and use in sampling surface.

Microbial concentration on a surface is measured in Relative Light Units (RLUs). A measure above the set threshold for RLUs would yield a positive ATP test that indicates that a surface has not been properly disinfected (Sanna et al., 2018). ATP bioluminescence systems use a special swab, which already has the test rinsing buffer and luciferin-luciferase reagent added, to test the area. The presence of bioluminescence, indicating a positive result, is detected using a luminometer with the intensity of the signal linked to the level of disinfection; results are available in seconds. A quality control swab from a surface that has been properly disinfected is used to calibrate the ATP luminometer.

ATP testing requires some technical training to ensure consistency in sampling different surfaces (e.g., bathrooms, armrests, tables in food courts, aircraft cabin surfaces, etc.). This testing method could be a valuable tool to compare the effectiveness of different disinfection technologies (like regular surface wiping versus electrolyzing disinfecting agents in the air for surface cleaning) to inform decisions about the most cost-effective and feasible disinfection equipment and practices for every environment.

4.1.3 UV Disinfection

Ultraviolet (UV) radiation is being tested by several airports to sanitize surfaces; sanitizing lowers the number of microbes on surfaces or objects to a safe level, as judged by public health standards or requirements. Germicidal UV (GUV) uses UV radiation to kill or inactivate bacteria, mold, spores, fungi, and viruses; it uses short wavelengths known as UV-C that are emitted in the 200-280 nanometer (nm) range, which effectively disinfect surfaces and aerosols. UV-C disinfection is proven to reduce bacterial and viral contamination in health care facilities and is used for surface and air disinfection (Duan et al., 2003; Andersen et al., 2006; Mphaphlele et al., 2015; Pavia et al., 2018; Dexter et al., 2020). Studies have found SARS-CoV-2 to be susceptible to inactivation by UV-C light (Buonanno et al., 2020; Heilingloh et al., 2020; Kitagawa et al., 2020).

UV-C inactivates a virus when high-energy photons interact photochemically with its nucleic acids (RNA or DNA), making them non-infectious. When applied at 254 nm wavelength and intensity 10-14 J/m^2, UV-C was shown to be at least 95% effective in inactivating viruses and killing bacteria (McDevitt et al., 2012). A new UV-C system with a 222 nm wavelength is considered safer for direct use due to minimal tissue penetration (Barnard et al., 2020; Buonanno et al., 2020; IES, 2020), and can be used to provide air and surface disinfection throughout irradiated spaces. This system might be suitable for surface disinfection in queues, food courts, bars, restaurants, store counters, and other surfaces typically found in airport terminal buildings (IES, 2020).).

UV disinfection can be an effective standalone method if ‘shadowing’, i.e., caused by objects blocking the emitted radiation from reaching the surfaces in some areas of the room, is accounted for; if not, it should only be used as a supplemental disinfection method (Andersen et al., 2006). A commercial UV-C system might also take longer to clean surfaces than regular surface disinfection. For example, a 254 nm UV-C commercial system used at a food disinfection facility took one hour to clean 1250 square feet compared to a trained worker who took approximately 23 minutes; there were no detectable differences in disinfection performance (Longsworth, 2020).

4.1.4 Antimicrobial Coatings and Materials

Airports are exploring the use of antimicrobial coatings and materials containing active ingredients that can inactivate viruses (Beyth et al., 2015). These usually need a longer time to reduce the viral load than disinfection methods and therefore have a different application profile, e.g., low touch surfaces and areas that are not disinfected often. Typically, physical cleaning would still be needed so that any deposited infectious matter in contact with the material is removed. There are two main groups of antimicrobial coatings:

- Inorganic antimicrobial materials, such as metals and metal oxides, e.g., silver (Ag), iron oxide (Fe_3O_4), titanium dioxide (TiO_2), copper oxide (CuO), and zinc oxide (ZnO); their properties are described in Table 4.1. These materials interact electrostatically with virus (and bacterial) membranes by releasing free radicals that hinder protein function and cause nucleic acid destruction. Most metal oxide nanoparticles exhibit antimicrobial properties through reactive oxygen species (ROS) generation, although some are effective due to their physical structure and metal ion release (Beyth et al., 2015). Copper, in particular, has been shown to be effective in inactivating a wide variety of viruses and bacteria. However, it is expensive, and no evidence has been found to suggest that it (or any other metal) prevents the spread of bacteria or viruses (Ben-Shmuel et al., 2020). This is because the anti-microbial effect of metals occurs over a period of hours to days, unlike chemical disinfectants that inactivate microbes in a matter of a few seconds to minutes. Thus, in a public setting, such as an airport terminal, where many people may touch the same metallic surface in a short period, not enough time will have elapsed for the anti-microbial properties to be effective.

- Polymeric (organic) antimicrobial materials can kill microorganisms by releasing antibiotics or antimicrobial peptides, or by acting as contact-killing surfaces; other materials used are quaternary ammonium compounds, alkyl pyridiniums, triclosan, chitosan, organometallic polymers, or quaternary phosphonium (see Table 4.1).

Table 4.1 List of Common Organic and Inorganic Antimicrobials (Adapted from Dastjerdi & Montazer, 2010 and Beyth et al., 2015)

Antimicrobial Material	Main Features	Applications
Silver (Ag)	Non-toxic, good electrical conductivity, expensive material	Used as a colloidal silver suspension or applied as a silver nanoparticle in clothing, textiles, consumer electronics, and appliances.
Iron Oxide (Fe_3O_4)	Inert material, anti-adherent properties, inexpensive	Applied as nanoparticles, it is a microbial inhibitor. Vehicle for other antimicrobials, helps in drug delivery and bacterial detection.
Titanium Oxide (TiO_2)	Has a photocatalytic activity, inexpensive material	Kills all types of bacteria and inactivates viruses. Used for UV protection and self-cleaning surfaces
Copper Oxide (CuO)	Non-toxic, good electrical conductivity, relatively inexpensive material	Applied as a nanoparticle, it has the strongest bonding capacity to bacteria and the highest bactericidal effect. Used as a direct coating for commercial surfaces or mixed with polymers to give consumer products and textiles long-lasting antimicrobial properties.
Zinc Oxide (ZnO)	Has a photocatalytic activity	Applied as a nanoparticle, it is an antimicrobial used in textiles
Quaternary Ammonium	Strong lipophilicity, cationic surfactant	Mixed with polymers to act as an antiviral, antibacterial, and antifungal material for consumer products, building components, and biomedical products.
Triclosan	Non-ionic broad-spectrum agent, non-toxic	Usually mixed with a solvent like water, gel, or organic compound. Used in personal care products like deodorants, oral care, shower gels, and handwashes.
Chitosan	Good biocompatibility, non-toxic, low immunogenicity	Biocompatible antimicrobial agent, it is a hydrophilic biopolymer used in the food and biomedical applications.

4.1.5 Hand Hygiene and Sanitation Stations in Airports

Intact skin (i.e., no open wounds, chapped skin, abrasions, etc.) is an effective barrier and is not a conduit for transmission of SARS-CoV-2. It is however possible to become infected when the virus is conveyed by the hand to the mucous membranes of the face (mouth, nose, and/or eyes). People can defend themselves against indirect transmission via fomites by reducing contact with surfaces and using appropriate hand hygiene (WHO, 2020).

Hand hygiene means to wash or sanitize hands regularly and adequately. During handwashing, soap should cover all the surfaces of both hands (including the back of the hand and under the nails) for 20 seconds or more (Rutala et al., 2008; Freeman et al., 2014; Pradham et al., 2020; Wölfel et al., 2020). Hand sanitizers that contain at least 60% alcohol can be used if handwashing facilities are not readily available. **Soap and the active ingredients in disinfectants destroy the protein protective layer of the SARS-CoV-2 virus with an effectiveness of more than 99.9% in less than 1 minute** (Van Doremalen et al., 2020).

Airports have increased the use of hand sanitation stations in both public areas and employee-only spaces to encourage people to disinfect their hands; some of these stations are hands-free and apply disinfectants directly (see Figure 4.2). Where handwashing or disinfection stations are not readily available, travelers may consider carrying and using their own hand sanitizer and/or disinfectant wipes. SARS-CoV-2 might still survive for several hours on people's hands (Hirose et al., 2020), so, travelers should avoid touching their eyes, nose, and mouth as much as possible when proper hand hygiene is not feasible. **It is recommended that hands be disinfected after touching high-touch surfaces such as door handles, elevator buttons, faucets, self-service kiosks, point-of-sale keypads, and luggage carts using appropriate sanitizers.**

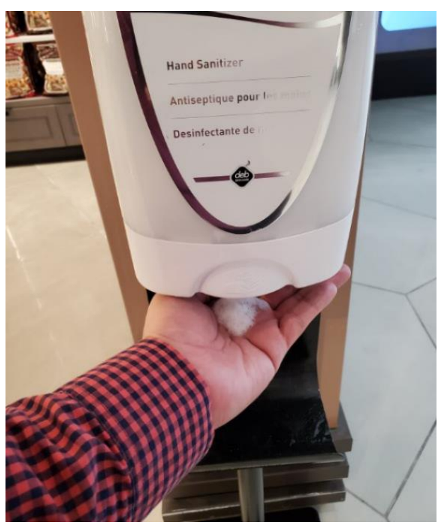

Figure 4.2 Hands-free disinfecting station in an airport.

4.1.6 Examples of Contactless Technologies for Possible Use in High Touch Areas

The incidence of COVID-19 infection through fomites is reduced by avoiding contact with frequently touched surfaces (WHO, 2020b). Contactless systems reduce the likelihood of people touching a surface used frequently that would require disinfection ideally after every use (WHO, 2020). In order to support this objective, airports, airlines and other airport tenants have increasingly invested in new technologies to enhance the contactless experience for travelers and staff. These technologies may be useful in high-traffic areas where contact with contaminated surfaces might present an exposure risk. Some of these technologies are still in development or have only recently become more widely available. As such, this is an evolving area and suitability and practicality of deployment may need to be determined.

- *Biometrics and contactless systems for checking-in*. Airports and airlines have invested in technology to support contactless systems for check-in, and interest in contactless systems has heightened during this pandemic.

- *Smartphone enhanced identification at security checkpoints.* Travelers may apply to enroll in one of many government Trusted Traveler Programs (e.g., in the U.S. https://ttp.dhs.gov/) to expedite screening at security checkpoints and international border processing. Mobile Passport Control (MPC) and other contactless methods of providing identity documents for enhanced security and efficiency are available. Since the pandemic, airports in the U.S. with the Department of Homeland Security (DHS) and Transportation Security Administration (TSA) have been working together to accelerate the deployment of Credential Authentication Technology (CAT) which began in 2019, as well as CAT with facial recognition cameras.

- *Smart applications for ordering food within the airport.* Some airports have introduced food delivery services that eliminate the need to go into a restaurant or fast food stall within the terminal. Applications (apps) for smartphones, tablets, or Quick Response (QR) codes are used that allow travelers to select their food, pay, and schedule pick-up or delivery in the terminal (see Figure 4.3).

Figure 4.3 Systems to enable contactless food ordering and delivery in airport terminal buildings.

- *Electronic contactless payments for shopping and dining.* Travelers may shop or purchase food using contactless payment systems enabled by credit or debit cards (see Figure 4.4) using near-field communication or radio frequency identification. Such systems also expedite payment, which reduces crowding and exposure time for airborne transmission of SARS-CoV-2 in airport stores, restaurants and fast food stalls.

Figure 4.4 Electronic contactless payment systems by card, smartphone or smartwatch.

- *Contactless restroom systems.* Restrooms at some airports have user detection sensors that control automated flushing systems for lavatories and urinals. Most of these restrooms offer contactless soap dispensers and faucets that enable proper handwashing without contact with potential fomites. In some cases, there are also contactless hygiene feedback systems to alert whether the bathroom requires attention by staff (see Figure 4.5).

Figure 4.5 Contactless faucet and feedback systems for cleanliness in restrooms.

4.2. SIGNAGE TO LIMIT CONTACTS AND INCREASE DISTANCES

Close contact transmission can occur when an infectious person sheds droplets that come into direct contact with an uninfected person's mucus membranes of the eyes, nose and/or mouth or are inhaled by that person. In this context, close is defined as within 6 feet (1.83 meters) as this is generally thought to be the range outside of which most larger droplets would fall to the ground (see Figure 4.6). There is convincing evidence of SARS-CoV-2 transmission via droplet and aerosol when people are in close contact (CDC, 2020a). Practices that support physical distancing, such as floor decals or physical barriers, are risk mitigation responses to this mode of transmission.

Airports use signs and floor stickers to indicate distances 6 feet (1.83 meters) apart in order to help people maintain physical distancing and reduce the likelihood of close contact transmission. This is especially important while queueing, e.g., in the ticketing area or security checkpoint (Figure 4.7), while waiting for food in restaurants (Figure 4.8), and when waiting at the boarding gate (Figure 4.9). While effectiveness relies upon compliance, such signs are useful reminders to travelers of risk mitigation measures in action by the airport. **It is recommended that signs be placed in as many spots as possible, on floors, chairs, walls, tables, posts, hallways or any other area where congestion and queues are likely to occur.**

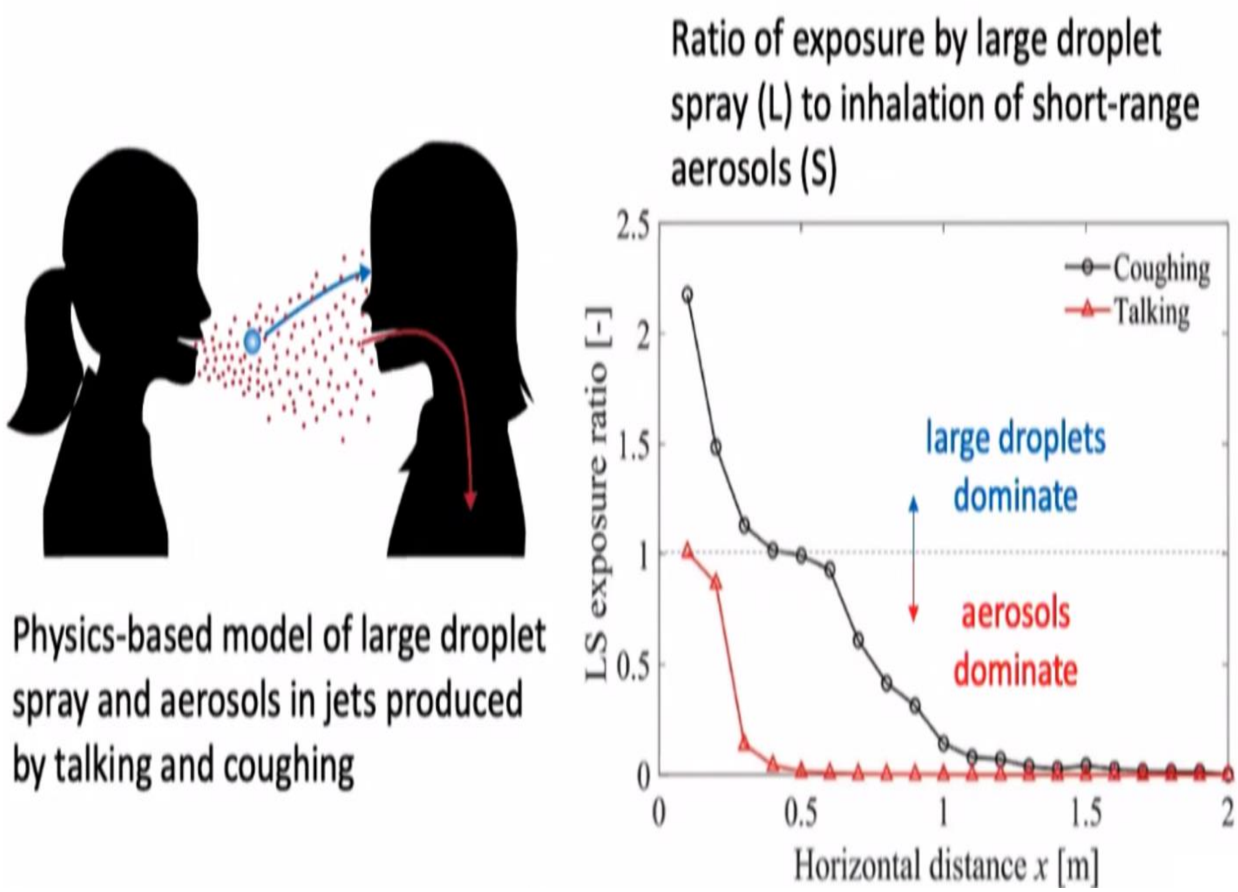

Figure 4.6 Range of large droplets shed by coughing and talking (Marr, 2020; Chen et al., 2020)

Figure 4.7 Floor signs to indicate physical distancing at airport ticketing area

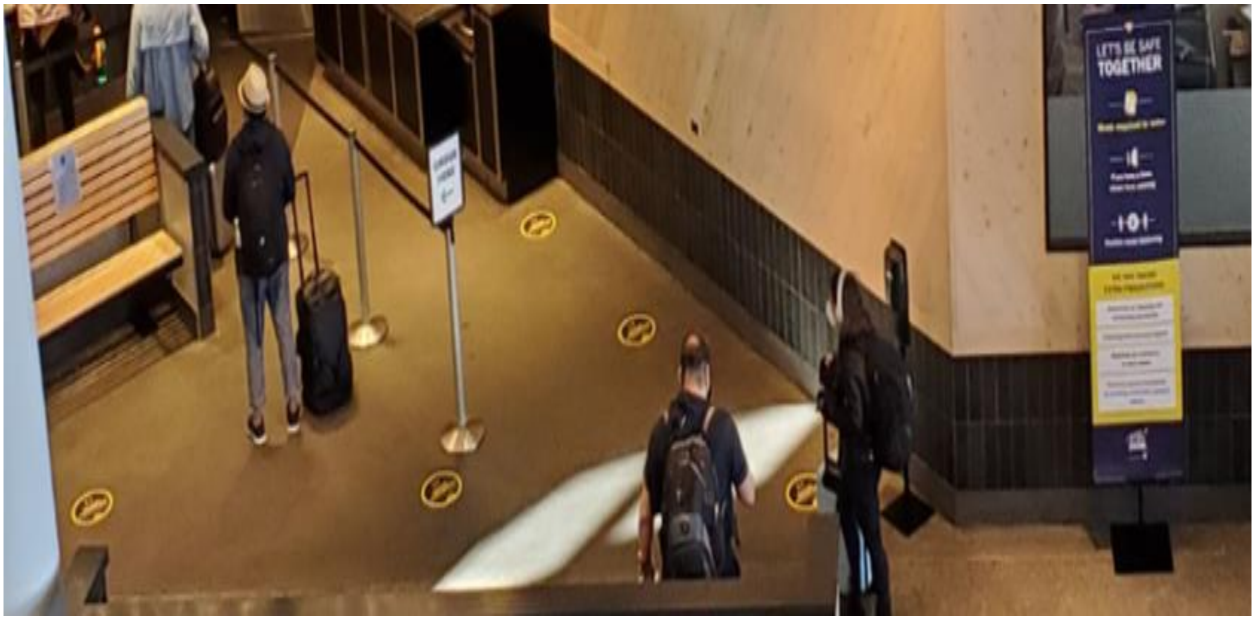

Figure 4.8 Floor signals for physical distancing enhanced by smartphone tracking of food order at an airport fast-food restaurant.

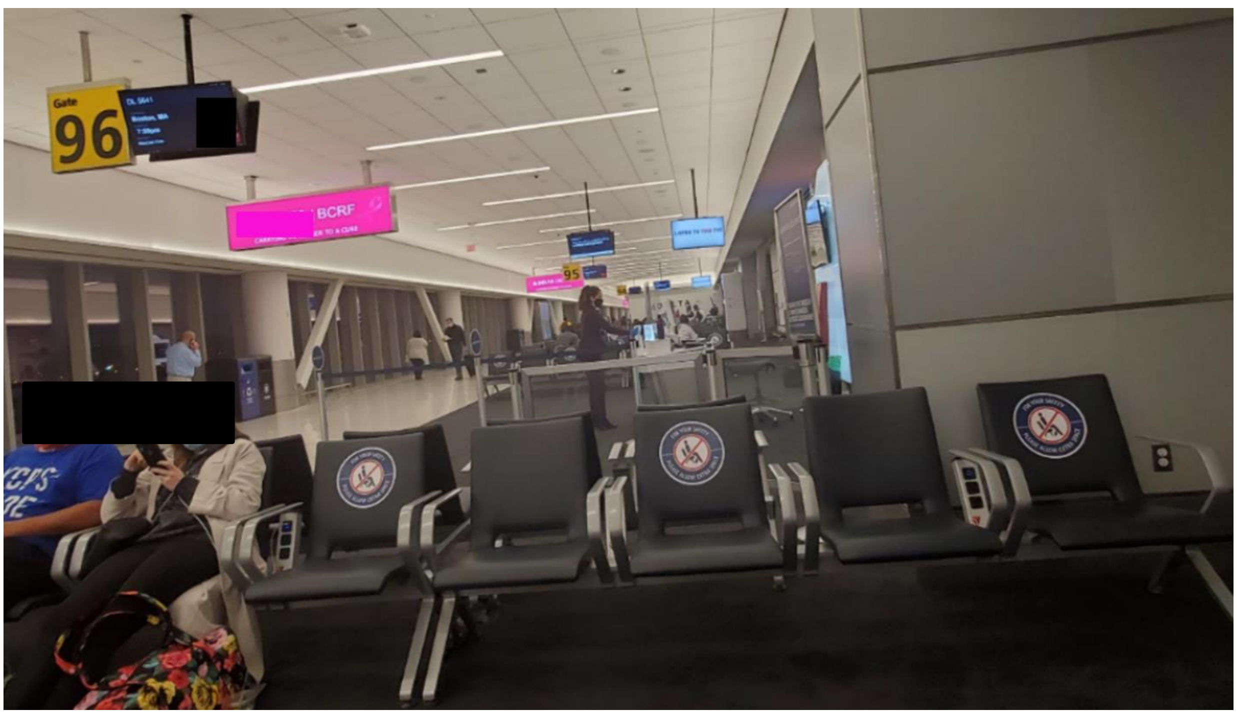

Figure 4.9 Labels to signal physical distancing on back rests for chairs at boarding gates.

4.3. CRITICAL EVALUATION OF THE COMBINATION OF VARIOUS RISK MITIGATION STRATEGIES IN VARIOUS 'TARGET' AIRPORT SETTINGS: MONTE CARLO ANALYSIS

The layered approach to risk mitigation of SARS-CoV-2 transmission in airport terminals relies upon the application of a range of practices used together or in sequence to reduce the probability that SARS-CoV-2 is passed from an infectious person to an uninfected person (see Chapter 2). A **Monte Carlo Analysis** (EPA, 1998) is a risk management technique used to conduct a quantitative analysis of risk. The process to characterize uncertainty by applying penalties to increase the variation of statistical functions for data points used in a Monte Carlo analysis is described in Appendix G. As a statistical tool, it can be used to calculate the theoretical effectiveness of different practices in the layered approach relevant to risk mitigation of SARS-CoV-2 transmission. Using this approach, effectiveness values for different Non-Pharmaceutical Interventions (NPIs) were drawn from science-based reports or technical tests described in the literature or through modelling undertaken for this report. The evaluation of benefits/risk reduction potential are determined in the absence of business considerations related to costs or implementation in airport setting – as such, there are issues of cost-effectiveness and practicality that would need to be determined if outcomes from the model are translated into the real-world. This information is provided to demonstrate the interaction of various options.

To explore the risk reduction potential of the layering approach in varying areas encountered during the Curb-to-Curb journey, this assessment focuses on the following distinct segments:

1. Check-in area
2. Security checkpoint
3. Airport shops
4. Eating (dine-in restaurants, fast-food restaurants, food courts, etc.)
5. Boarding gates

For each of these segments, three scenarios were explored: a base-case, an-enhanced case, and an augmented-case. Appendix G provides the full results and the specific conditions for each of the three scenarios in each of the five segments.

Table 4.2 shows the percentage risk reduction under three generic risk mitigation scenarios as follows:

- **Base-case scenario**. Assumes pre-COVID conditions where there was no health attestation, no screening for symptoms, no SARS-CoV-2 testing, no mask wearing, normal surface cleaning and disinfection, code compliant ventilation, normal height ceilings, code compliant air filters installed (MERV 8), no air disinfection, no signage to maintain physical distancing, no physical barriers, no technologies for crowd control, no contactless procedures in use.

- **Enhanced-case scenario**. Assumes health attestation was undertaken, no screening for symptoms, no SARS-CoV-2 testing, all individuals wear a non-surgical cloth mask, enhanced surface disinfection and standard ventilation, ceilings are medium (8-14 feet/2.4-4.3 meters) or high (>14 feet/4.3 meters) dependent on the characteristics of the space (in the check-in and food court scenarios, it is assumed both spaces have high ceilings), MERV 13 air filters were installed, signage to maintain physical distancing was in place, no physical barriers, some technologies for crowd control, some contactless procedures in use.

- **Augmented-case scenario**. Assumes health attestation was undertaken, no body temperature screening by thermal cameras, rapid SARS-CoV-2 testing onsite, all individuals wear a non-surgical cloth mask, enhanced surface disinfection, good ventilation, high ceilings, MERV 13 air filters, signage to maintain physical distancing, physical barriers were in place for crowd control and/or contactless procedures were in place.

The base-case as described here will generally represent the conditions that existed in these segments at airport terminal buildings *prior* to airports putting in place the different NPIs to respond to the COVID-19 pandemic. The enhanced-case scenario largely represents the application of a set of NPIs relatively typical of those being employed by airports in response to the current pandemic. The augmented-case scenario represents maximally applied NPI under optimal conditions unlikely to be achievable over time in a real-world setting. However, presenting the enhanced-case and augmented-case is intended to help illustrate the situation airports may face in considering the relative effectiveness of applying a broader array of NPIs in various areas of an airport, taking into account that variations within and among airports may make certain NPIs more practicable and effective in certain settings than others.

For all segments, there was significant risk reduction between the base-case and enhanced-case scenarios, i.e. showing the effectiveness of a layered NPI strategy. However, there was only a marginal difference between the enhanced-case and the augmented-case scenarios. This analysis can be helpful for airport operators in determining return on risk mitigation investments.

Table 4.2 Percentage Risk Mitigation Calculated Under Three Different Risk-mitigation Scenarios Across Five Segments of the Airport Curb-to-Curb Journey

Segment of Curb-to-Curb Journey	Risk-mitigation Scenarios (% reduction)		
	Base	Enhanced	Augmented
1. Check-in area	61.48	100.0	100.0
2. Security checkpoint	55.14	99.26	99.93
3. Airport Shops	54.33	98.46	99.87
4. Eating a) dine-in at a restaurant b) ordered from fast-food restaurants and/or and eating at food courts, etc.)	a) 55.14 b) 61.48	a) 97.66 b) 100.0	a) 99.84 b) 100.0
c) Boarding gates	52.65	99.09	99.93

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5.0 VIRAL TESTING

SARS-CoV-2 testing can help identify persons infected with the virus, including those who are asymptomatic. It is therefore an important part of an overall risk reduction strategy (Airlines for America, 2021). Diagnostic clinical tests for SARS-CoV-2 are generally performed if there are reasons to suspect an individual may be infected, such as where someone displays symptoms or has had recent contact with a case, and to determine resolution of an active infection (CDC, 2020). **In the setting of air travel, testing should be viewed as a public health screening measure rather than a diagnostic clinical tool, with the more limited but important goal of identifying infected travelers and keeping them out of airports and off the aircraft.** This is enabled by the unique setup of air travel, for example, few entry points compared to other modes of transportation like subways, wait times between arrival at the airport and departure, the existing security system and passenger acceptance of these security measures and existing land side/air side infrastructure.

In assessing the utility of tests, two key attributes are considered important (Watson et al., 2020):

- **Specificity** shows the true negative rate, i.e., it represents the proportion of negative tests among people who are actually negative for SARS-CoV-2.
- **Sensitivity** reveals how often a test generates a positive result for people who actually have SARS-CoV-2, i.e., the true positive rate.

The U.S. Food and Drug Administration (FDA) has granted Emergency Use Authorization (EUA) (FDA, 2020) to a number of SARS-CoV-2 tests, including molecular Real-Time Reverse Transcription Polymerase Chain Reaction (RT–PCR)-based tests, molecular loop-mediated isothermal amplification (RT-LAMP)-based tests, transcription mediated amplification (TMA)-based tests, and antigen tests. The FDA alerted clinical laboratory and healthcare staff on January 8, 2021, that false negative results may occur with any molecular test used for the detection of SARS-CoV-2 where a mutation had occurred in the part of the virus' genome assessed by that test (FDA, 2021). It is monitoring whether the known variants or strains of SARS-CoV-2, including the variants recently identified in the United Kingdom (B.1.1.7), South Africa (B.1.351) and Brazil (B.1.1.28) can be detected by available tests approved for EUA (CDC, 2021). None of the routine tests differentiates among variants or strains, which requires a detailed genomic analysis undertaken in a laboratory setting using Next Generation Sequencing (NGS) tests (Deng et al, 2020; Gonzales-Reiche et al., 2020).

RT-PCR tests, use a PCR machine (typically housed in a laboratory) to run a series of reactions to detect the genetic material or nucleic acid of the virus. SARS-CoV-2 is an RNA virus (see Chapter 2), and the PCR converts its ribonucleic acid (RNA) into deoxyribonucleic acid (DNA). This is then amplified by the PCR to make millions of copies of the DNA. The test then detects a specific segment of this DNA. The amplification cycles allow the test to detect very low levels of viral genetic material, so RT-PCR tests are highly sensitive, i.e., they efficiently detect the true positives and give a low rate of false negatives. The number of amplification cycles needed for a test to rise above the limit of detection of the test is called the cycle threshold (Ct) value. Ct values are inversely proportional to the amount of target DNA in a sample, i.e., how much virus an infected person harbors; the lower the Ct value, the more infectious an individual is predicted to be. Studies have demonstrated that RT-PCR samples with Ct values of 35 or greater are unlikely to have sufficient viable virus to be a transmission risk (Jaafar et al., 2020). Data for Ct values suggest that some infected individuals might be superspreaders (Sarkar et al., 2020). A RT-PCR test may be performed in six to 12 hours, but results may take several days to be made available given the current high demand and sample backlog.

RT-PCR tests are highly specific, in that the rate of false positives are low (but not zero, especially considering the sample logistics and risks of cross-contamination or misidentification) (FDA, 2020a). Due to their high sensitivity and specificity, RT-PCR tests are generally considered the 'gold standard' for clinical diagnostic detection of SARS-CoV-2 (CDC, 2020a). However, it is not without issue (Surkova et al., 2020). **The high sensitivity of RT-PCR tests mean they may not be ideal for public health screening, for example in situations where permission to board a flight is based upon such a test.** This is because RT-PCR tests do not distinguish between replicating virus (i.e., the person is infectious) and the presence of remnants of viral RNA/DNA that will be present even after an infected person is no longer infectious (AAFP, 2020). Indeed, infected individuals may test positive with RT-PCR for several weeks after they are no longer infectious given the test continues to detect genetic material from inactive viral debris (Service, 2020). **In a situation where testing at an airport or before a flight is undertaken using RT-PCR, this could mean a person who has recovered from COVID-19 but still has remnants of the virus nucleic acid in their system could be barred from traveling.** Some strategies that could help alleviate this problem, for example bringing a dated test result with a physician's note stating that the person has recovered and is no longer experiencing symptoms or providing proof of a positive antibody test to demonstrate recovery (noting however that there are known cases of persons being infected a second time with SARS-CoV-2; Ledford, 2020). Regardless of these issues, permission to board some flights and enter some U.S. states and countries is currently predicated upon demonstrating a negative RT-PCR test. As such, there is likely to be ongoing demand for access to RT-PCR tests by travelers.

LAMP-based tests, as in the case of RT-PCR tests, detect viral RNA but the amplification cycle used to generate the DNA copies does not require the heating and cooling reactions of the RT-PCR tests. Test samples can therefore be processed in non-laboratory settings using an instrument that can confirm the presence of SARS-CoV-2 RNA in under 30 minutes. LAMP tests have similar sensitivity and specificity to RT-PCR tests (Thompson & Lei, 2020). This means their use in public health surveillance settings, comes with a similar concern as to widespread use of RT-PCR—namely finding remnants of viral nucleic acid in persons no longer in the active phase of a COVID-19 infection.

TMA-based tests, similar to LAMP-based tests, amplify viral RNA without temperature changes, which allows tests to be conducted with fewer steps and processing time. Additionally, TMA-based tests have similar sensitivity and specificity when compared to RT-PCR tests (Gorzalski et al., 2020).

Antigen tests detect one or more specific proteins from a virus particle, typically the N protein for SARS-CoV-2, and tend to be highly specific. As such, they can be used to identify patients with COVID-19 but are typically less sensitive than RT-PCR tests. **All currently authorized antigen tests are point of care (POC) tests**. POC tests can be used in various settings, typically provide results in under an hour and can be used to extend testing to communities and populations. The first antigen tests to receive FDA EUAs had sensitivity in the range 84.0 to 97.6%. This compares favorably with RT-PCR tests with a sensitivity close to 100%, albeit lower for early stage infections. A recent study of the Abbott BinaxNOW antigen test suggests that it identifies most of the highly infectious individuals (e.g., Ct <30), with good sensitivity (93.3%, 95% confidence interval [CI]: 68.1 to 99.8%), and high specificity (99.9%, 95% CI: 99.4 to 99.9%) (Pilawoski et al., 2020). However, this data is based on symptomatic populations and it is noted that the travel population are by default assumed healthy and/or asymptomatic. In studies of asymptomatic populations, research from the United Kingdom demonstrates that certain antigen tests have low false positive rates and good sensitivity when compared to RT-PCR (Peto, 2021).

With sensitivity and specificity levels near RT-PCR tests levels, false positive results are unlikely with antigen tests. They can also be used to identify those individuals with a high viral load, i.e., pre-symptomatic and early symptomatic cases, which likely accounts for a significant proportion of transmissions (CDC, 2020b). This is important. Essentially, comparing antigen tests to RT-PCR is not necessarily relevant, as RT-PCR is likely to find positive results that are no longer infectious (or not as likely to be highly infectious). However, antigen levels in specimens collected beyond five to seven days after the onset of symptoms may drop below the test detection limit, beyond which individuals are more likely to have lower viral loads and thus a lower probability of passing the virus to others (CDC, 2020b; WHO, 2020b). Use of antigen tests before a planned flight, at home via tele-medicine observation, in a supervised off-site location or in an airport setting, offers the potential for quickly identifying positive COVID-19 cases, which in turn will help to minimize risks of exposure during travel.

When comparing the attributes of the different tests, the purpose of the testing program needs to be considered. If the question is diagnostic, that is, “Has this individual been infected recently, regardless of their current infectivity?”, then RT-PCR is the best method. However, if the question is, **"Is this individual infectious now?", which is highly relevant to air travel, then the antigen test provides the answer quickly**. Use of the antigen test can also help avoid misleading assumptions of transmission risk long after the relatively brief infectious period, estimated to be between seven and 14 days for SARS-CoV-2 (Byrne, et al, 2020). Given RT-PCR-based tests can be misleading for travel purposes, yielding positive results days or weeks after the infectious period has passed, a practical recommendation would be to use an antigen test as a POC test as close to departure as possible. A challenge with the widespread use of antigen tests, at this time, is ensuring adequate availability of test kits to meet the widespread demand for populations at schools, elder care facilities and essential services in addition to travelers. However, as antigen tests become more readily available, various testing strategies become more appropriate for general use.

Beyond the sensitivity, specificity and expected turnaround time of the testing regimen, specimen collection method is a critical consideration. For use in screening tests, the ease of sample collection is key. Most types of specimen collection would need to be undertaken by, or under the supervision of, trained healthcare personnel. However, some tests use saliva samples or nasal swabs and lend themselves to self-collection. Depending on the type of test, the following are acceptable test specimens (CDC, 2020a):

- A nasopharyngeal specimen collected by trained healthcare personnel.
- An oropharyngeal specimen collected by trained healthcare personnel.
- A nasal mid-turbinate swab collected by trained healthcare personnel or by supervised on-site self-collection (using a flocked tapered swab).
- An anterior nares (nasal swab) specimen collected by trained healthcare personnel, or self-collected under observation by healthcare personnel, or at home or on-site self-collection (using a flocked or spun polyester swab).
- Nasopharyngeal wash/aspirate or nasal wash/aspirate specimen collected by trained healthcare personnel.
- A saliva specimen collected either by the person being tested, at home or at a testing site under supervision.

5.1 TESTING CONSIDERATIONS AND STRATEGIES

Currently, the molecular tests (e.g., RT-PCR, LAMP, and TMA) and antigen tests with EUAs from the FDA are authorized for diagnostic testing on *symptomatic* persons within the first five to 12 days of the onset of symptoms and have historically required a prescription from a licensed healthcare practitioner. However, the U.S. government has provided guidance confirming that testing of *asymptomatic* individuals with POC tests using anterior nares specimen collection or via self-collection is allowable for screening in congregate facilities (CMS, 2020; HHS, 2020); **this type of self-collection could be applicable in aviation settings as well.**

The availability, type, and cost of testing is changing rapidly as states and local health departments adapt to changing local circumstances (AAFP, 2020). As of January 21, 2021, testing for individuals who do not have COVID-19 symptoms (also called asymptomatic testing or surveillance testing) is not being offered routinely in all geographic regions. Where available, costs for asymptomatic tests, where insurance or an employer is not covering the costs, is in the range of U.S. $60 to $300 (WSJ, 2020).

Individuals interested in or required to submit to travel-related testing often face obstacles due to the lack of access to asymptomatic testing programs, associated costs, and the need for test results in a specified timeframe, usually 48 hours prior to travel. A major concern is that adequate testing supplies are not currently available to accommodate all travelers. In the meantime, some airlines have established testing programs to support travel to locations with specific requirements—with some allowing their customers traveling to any location to purchase the test. As of publication, these programs are limited to specific airports, specific flights or specific airlines. In some cases, these are trial programs with an associated fee. The CDC issued new requirements, effective January 26, 2021, that all inbound international travelers to the U.S. will be required to present a negative molecular and/or antigen test (CDC, 2021a); this built upon their December 28, 2020, requirement that applied to the United Kingdom only given the emergence of the SARS-CoV-2 variant (CDC, 2020c). Canada rolled out its own requirement on January 7, 2021 and other countries are following suit. These developments have significantly increased the demand for pre-departure testing capacity well beyond the more localized requirements circa Summer/Fall 2020. While adequate testing supplies might not be available now, there are indications that testing supplies will likely be available at some point in 2021. This is an ever-evolving situation and should be reviewed on a regular basis.

To determine when and what type of testing could be most efficacious for travelers, two components of a trip are considered that have possible disease transmission risks. Firstly, the time during travel, i.e., time at the airport and on the aircraft. Secondly, the time after travel is complete, i.e., post travel, and includes potential translocation of infection to a new geographical location. However, in many cases, the type of testing is specified by the destination or is a government-enacted requirement. This is a rapidly changing landscape, with a negative RT-PCR test required when traveling to certain U.S. states in order to avoid or reduce the quarantine time, for example in Connecticut where it will exempt the person from quarantine (Brown & Marples, 2021).

A number of studies have used mathematical models to evaluate testing and quarantine strategies that consider both the period of travel and the period after a trip (Clifford et al., 2020; Johansson et al., 2020; Quilty et al., 2020; Wells et al., 2020). Modeling by the Centers for Disease Control and Prevention (CDC), and forming the basis of its recommendations, concludes that testing one to three days *before* departure and three to five days *after* arrival for both domestic and international travel are optimal (CDC, 2020d; CDC, 2020e; Johannson et al., 2020). They recommend that pre-travel testing be undertaken as close to the time of travel as possible to minimize the risk of an exposure event occurring after the test but before travel, or the development of a detectable infection during that period. This type of pre-and post-testing process is most effective in minimizing the potential for translocation of SARS-CoV-2.

Several other approaches can be used to minimize the risk of translocation of infection (AARP, 2020). Both the CDC and the World Health Organization (WHO) state that 14-days is the most protective quarantine period (CDC, 2020d; CDC, 2020e; WHO, 2020). Modeling studies show that combinations of shorter quarantine periods and testing could be nearly as effective as a longer quarantine period, especially after accounting for compliance with quarantine protocols (Clifford et al., 2020; Johannson et al., 2020). Based on modeling, the November 2020 CDC guidance states that quarantining upon arrival for seven days (in conjunction with post-travel testing at three to five days) is nearly as effective as a 14-day quarantine period (CDC, 2020d; CDC, 2020e). The three to five-day post travel period accommodates viral dynamics, i.e., an incubation period, assuming an individual was exposed immediately prior to travel or during travel (Johannson et al., 2020). **Immediate testing upon arrival provides minimal added benefit if initial testing was conducted just before travel.**

At this stage of the pandemic, there are several reasons to question the value of post-travel testing and quarantine programs in most settings, including:

- Testing and quarantine may have only limited impact on reducing the risk of spread (i.e., translocation), particularly with respect to travel between areas of similar infection prevalence. For example, if the number of cases identified with pre-travel testing were lower in incidence than in the local community, it would appear that travelers would not increase the risk of transmission beyond those already in the community (ICAO, 2020).

- Given the current widespread nature of the pandemic, there is limited evidence that the importation of cases is contributing to the ongoing spread of the virus (EASA, 2020).

- The prevalence of infection in travelers (non-symptomatic subpopulation due to pre-travel screening, testing, etc.) is potentially lower than in the general population (EASA, 2020).

- The CDC and others acknowledge monitoring compliance with quarantining is a challenge and therefore, given the other considerations, countries and organizations need to consider if implementing quarantine programs is the most effective use of scarce resources as well as its economic, social, and other negative health impacts (Johannson et al., 2020).

5.2 TESTING RECOMMENDATIONS

The U.S. interagency 'Runway to Recovery' report (U.S. Departments of Transportation, Homeland Security, and Health and Human Services, 2020) recommend that pre-departure testing should occur prior to both the outbound and the inbound flight of a roundtrip itinerary. Requiring pre-travel SARS-CoV-2 testing for all travelers would not guarantee completely that all of them would be free of infection. However, as part of a layered risk reduction approach, pre-departure testing could help reduce the risk of travel-related transmission. At this time, various test-and-travel strategies demonstrate both strengths and weaknesses. Therefore, **if the primary goal is to reduce individual-level risk during travel, pre-travel testing should be performed as close to the travel event as possible, i.e., within 24 hours, using a test with appropriate sensitivity and specificity** (Kiang et al., 2020). The International Civil Aviation Organization (ICAO) recommends that any test selected should have a minimum of 95% sensitivity and 95% specificity (ICAO, 2020). However, given the fact that no test can guarantee 100% accuracy, it is important to ensure that any testing protocol is included as part of the multi-layered application of carefully considered non-pharmaceutical interventions (NPIs) as discussed in this Curb-to-Curb report.

For the purposes of passenger and crew testing prior to a flight, antigen testing has several advantages over RT-PCR-based testing and rapid LAMP testing. Considerations include ease of specimen collection (antigen tests are available that use anterior nares swab or saliva), low risk of contamination or misidentification, and close association with active, infectious virus. However, since no test procedure is perfect and given RT-PCR-based tests can be misleading for travel purposes, remaining positive days or weeks after the infectious period has passed (see section 5.1), a positive PCR-based test could be followed by an antigen test. This is consistent with utilizing an orthogonal testing strategy as discussed in the CDC's Interim Guidelines for COVID-19 Antibody Testing (CDC, 2020f). For example, a positive PCR test combined with a negative antigen test means the individual is infected but no longer likely to be infectious; where an antigen test was negative, greater sensitivity can be achieved with a follow-up RT-PCR-based test

Given the shorter turnaround time, antigen tests have tremendous potential in providing immediate results even though they may have slightly lower sensitivity than RT-PCR tests (CDC, 2020; CDC, 2020a; CDC, 2020b). Due to the need for RT-PCR tests to be analyzed in a laboratory, the time lapse between testing and receiving test results does not accommodate the possibility that an individual can become exposed to the virus after taking the test but before traveling. Therefore, rapid antigen testing may serve a critical need in a layered approach to identify asymptomatic travelers or those with low-level symptoms (Larremore et al., 2020). Consequently, it is recommended that travelers should undertake an **antigen test as close to their time of travel, either the same day or one-day prior**. Travelers should, however, verify testing requirements in place at their intended destination as antigen testing might not be an acceptable alternative to a RT-PCR test. Of course, all recommendations being made regarding implementing mandatory testing strategies are dependent upon access to adequate supplies, having appropriate testing protocols that ensure the integrity of sample collection from the traveler, and consideration of costs, logistics and privacy issues.

As travelers have invested time and money in a trip, any testing scheme that is being used to support air travel should include contingencies for re-taking a test if the first result is positive. The follow-up test, either another antigen test from a different manufacturer or molecular test, could be used to evaluate whether a false positive has occurred or not (CDC, 2020f). If the second test is positive, the individual should not be allowed to travel. If the test is being done at the airport, the airport operator or airline should have policies and procedures in place in coordination with state and local public health authorities for the infectious individual to be immediately isolated and safely evacuated to a location that can provide isolation or treatment. Clearly, if testing were performed prior to arrival at the airport, as is the case in most current circumstances, then the airline or airport would not be involved in retesting.

5.3 VACCINE PROGRAMS AND TRAVEL 'PASSPORTS'

Vaccines work by training and preparing the body's immune system to recognize and fight off the microbe they target. As such, COVID-19 vaccines tackle the disease and do not necessarily control transmission of SARS-CoV-2 virus directly. The influence of vaccine programs on transmission risk is currently being studied in detail. While COVID-19 vaccines should become more widely available in 2021, there are still likely to be COVID-related travel restrictions in many countries for the near future. Under the International Health Regulations (IHR, 2005), countries can implement health measures that require travelers to provide vaccine certifications, but this requirement is limited to specific diseases and currently only includes yellow fever. As the WHO categorized the current COVID-19 pandemic as a public health emergency of international concern (PHEIC), it is allowable under international law for countries to require vaccine and/or testing in order to enter the country (WHO, 2020a). The interaction between testing and vaccination programs must also be considered, given the possibility of a recently vaccinated traveler being misidentified as having an active infection.

While countries may require evidence of vaccination, it is unclear how many will make this a requirement. Additionally, some segments of the population will choose not to get the vaccine. While confidence is increasing, a recent survey indicated that only 60% of the U.S. adult population will choose to be vaccinated (Pew Research Center, 2020). Therefore, while mass vaccination of the global population will greatly reduce the risks of spreading the disease, it may take considerable time before COVID-19 vaccines reduce the public health challenges related to travel. Continuous monitoring for persistence of immunity post vaccination and effectiveness against emerging variants of the SARS-CoV-2 virus will require sustained focus and adaptation of vaccination programs.

Countries are developing programs that allow travelers to provide proof of testing and/or vaccination (Phelan, 2020). Several organizations have developed smartphone application (app)-based technologies that could be used as a COVID-19 'passport'. For example, the International Air Transportation Association (IATA) has developed a COVID-19 'Travel Pass' (IATA, 2020) while the World Economic Forum and non-profit Commons Project Foundation jointly developed the 'CommonPass' (Commons Project, 2020). These technologies allow secure methods to confirm vaccine and/or testing history and any additional screening measures, such as a health declaration that may be required by the destination country. Each of these systems depends upon widespread adoption and, at this point, there is no indication that this will be the case. The real enabler for adoption of these systems is the definition of a standard and its mutual recognition; the same is true for testing.

5.4 RECOMMENDATIONS

Current guidance or requirements for testing and quarantine related to travel vary from country to country, and from state to state within the U.S., including the timing of the test prior to or after travel, the type of test used (molecular or antigen tests), and the use of negative test results to lift public health measures, such as quarantine. The myriad of different requirements results in traveler confusion and negatively affects both confidence in and the ability to travel. This has far-reaching economic impact worldwide. Therefore, **harmonization of testing protocols and requirements is critical to restoring passenger confidence in air travel.** This harmonization should be a collaborative undertaking by national governments, their health services, state and local health officials, airlines, and airport operators.

Testing regimes should be framed as part of a broader evaluation of the need to reduce risk across many daily, routine activities. In the U.S., adoption of consistent guidelines would improve situations where there is variability among U.S. state regulations. For airlines, POC antigen testing within 24 hours prior to a flight could be considered a component in the layered approach to reduce risk of SARS-CoV-2 transmission during travel. A current roadblock to implementing a program requiring testing of all travelers is the supply and availability of quality tests, while ensuring that limited supplies do not negatively affect other sections, such as schools and healthcare. With wide-scale immunization, the rationale for screening tests will gradually diminish, manifested by falling positivity rates among travelers. Eventually, the population prevalence of persons infected with SARS-CoV-2 is anticipated to reach a level when testing may become unnecessary. Until then, continuing to implement effective precautions while evaluating effective testing options for travelers provides an important tool for reducing disease transmission and encouraging confidence in the public health safety of the aviation system.

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6.0 HEALTH SCREENING

Health screening is a key tenet in the triad ‘Test-Trace-Isolate’ (CDC, 2020a) model for the control of infectious diseases. Infection with SARS-CoV-2 **causes a disease referred to as COVID-19**. The ability to identify people infected with COVID-19 (‘cases’), who are contagious (i.e., infectious) and then isolate them from non-infected persons is the most effective means of controlling transmission of SARS-CoV-2. For such screening, cases are identified either by viral testing or by health symptom screening, or a combination of both. **For travel by air, as with other public-facing activities during a pandemic, a self-assessment of health status should start *before* a person leaves their home; it is a critical component of an effective layered risk mitigation strategy**. However, a complicating factor with COVID-19 is that in the early phase of their infection people may not display any symptoms (i.e., **pre-symptomatic)**, while other people who are infected do not display any symptoms across the course of their disease (i.e., **asymptomatic**; Oran & Topol, 2020). As such, health screening based on symptoms is inherently limited in its effectiveness.

Typically, the ticket vendor and/or airline would advise travelers at the booking stage of their journey about the symptoms of COVID-19 and the importance of health self-screening close to their date of travel. Persons with symptoms indicative of COVID-19 and/or a positive SARS-CoV-2 test (see Chapter 5) would then not present themselves at an airport or expect to be able to board a flight. To the extent health screening is to be undertaken at an airport, protocols would need to be in place to manage those who are flagged as potentially infected.

6.1 SELF-SCREENING FOR COVID-19 RELATED HEALTH SYMPTOMS

Strategies for self-screening for COVID-19 health symptoms are important and represent an important aspect of a layered approach to help prevent transmission of SARS-CoV-2 while traveling. While several health symptom-screening methods are included here, only self-screening for COVID-19 health symptoms and health attestation to the airline concerned are currently in widespread use; temperature checks are used in some settings. Symptom screening can only be effective with identifiable COVID-19 symptoms and relies upon truthful attestation. Aviation industry members should generally adopt guidance from the Centers for Disease Control and Prevention (CDC) on COVID-19 symptoms, which at this time is considered the most comprehensive and current assessment of COVID-19 symptomatology (Burke et al., 2020; CDC, 2020b). The symptom list used by the aviation industry is consistent with the clinical characteristics of COVID-19 patients (Richardson et al., 2020; Wang et al., 2020).

Health self-assessment screening refers to the identification by a person of health symptoms consistent with COVID-19. This can be done by completing a survey tool and may include undertaking measurements of temperature and/or oxygen saturation levels at home if suitable equipment is available. People with COVID-like symptoms and their close contacts should be considered suspected or probable cases and self-quarantine until their infection status is determined clinically. The CDC identified a set of symptoms frequently associated with a COVID-19 infection (CDC, 2020b) that can be used to identify those who warrant further evaluation. The deCODE project in Iceland noted that fever, although the most prevalent symptom reported, was not present in the majority of true positive results (Gudbjartsson et al., 2020).

- Fever above 100.4 degrees Fahrenheit (°F) (38 degrees Celsius [°C]), or feeling unusually hot (if no thermometer is available), accompanied by shivering/chills
- Sore throat
- New cough not related to a chronic condition
- Runny/stuffy nose/nasal congestion (not related to allergies or relieved by antihistamines)
- Difficulty breathing, shortness of breath
- Diarrhea, with or without respiratory symptoms
- Nausea and/or vomiting
- Headache unrelated to chronic condition
- Fatigue
- Muscle aches
- New loss of sense of taste or smell
- New foot sores (COVID-19 toes) (Freeman, et al., 2020)
- New rash (Freeman et al., 2020)

Previous **travel to areas with high community prevalence of new COVID-19 infections** is a risk factor for air travelers and can be assessed during pre-check questionnaires. The CDC suggests that potential travelers consider if COVID-19 is spreading in their local community or planned destination as this might increase the chance of infecting others or becoming infected and that they check quarantine requirements (CDC, 2020c). High-risk areas are determined by a seven-day incidence rate per 100,000 people. A list of travel requirements for every community in the U.S. can be accessed at: https://www.cdc.gov/coronavirus/2019-ncov/travelers/travel-planner/index.html and for Europe at: https://www.ecdc.europa.eu/en/covid-19/situation-updates/weekly-maps-coordinated-restriction-free-movement?utm_source=POLITICO.EU&utm_campaign=a4fcda78ad-EMAIL_CAMPAIGN_2020_10_27_04_35&utm_medium=email&utm_term=0_10959edeb5-a4fcda78ad-189742041.

However, the effectiveness of self-attestation forms is limited since people infected with SARS-CoV-2 may be pre-symptomatic for several days (He et al., 2020) and 40 to 45% of SARS-CoV-2 infections are considered asymptomatic (Oran & Topol, 2020). The effectiveness of self-assessment questionnaires also relies on individuals either recognizing the symptoms, knowing others they have met are COVID-19 positive and being honest when they fill out their forms. However, screening for COVID-like symptoms is still a useful non-pharmaceutical intervention (NPI; see Chapter 4).

6.2 USE OF EXTERNAL DEVICES/MEANS FOR COVID-19 SYMPTOMS' SCREENING

As noted in section 6.1, while useful, there are limitations to self-screening for COVID-19 symptoms and subsequent health attestation. Therefore, supplementary screening tools can be used where practicable to improve the likelihood of detecting COVID-positive individuals. While the presence of fever, coughing, shortness of breath or low oxygen saturation levels are not definitive signs of COVID-19, screening for one or more of them could help identify people who should be tested, though there are limits and practical implementation challenges associated with their use. Combining some of these measures may be useful given an analysis of over 2.6 million participants in the U.S. and United Kingdom (U.K) who reported symptoms via a smartphone application (app) showed that several symptoms and indicators taken together, i.e., loss of smell and taste, severe or significant persistent cough, severe fatigue, and skipped meals, reliably predicted the likelihood of testing positive for the virus and being a confirmed case (Menni et al., 2020). Screening for these symptoms, in addition to gender and age, showed a sensitivity (the ability of a test to correctly identify patients with a disease) of 0.65 and 0.66 and a specificity (the ability of a test to correctly identify people without the disease) of 0.76 and 0.83, for U.K. and U.S. participants, respectively (Menni et al., 2020).

6.2.1 Measurement of Body Temperature

Measurement of body temperature is used in airports around the world as a screening tool for various diseases. It is somewhat useful in reducing the importation cases of some infectious diseases, such as Dengue Fever and Ebola that have short incubation periods and a high rate of associated fever (Guan et al., 2010; Kuan et al., 2010; Thwaites & Day, 2017) albeit neither are caused by respiratory-transmitted viruses. Medical grade or industrial grade infrared thermometers can be used at a minimum distance of one foot (30.5 cm) away from a passenger's forehead, which reduces contact but can be subject to false positives/negatives (CDC, 2020b).

The CDC recommends that if readings at or above 100.4°F (38°C) indicate a fever then the person should be prevented from entering an airport or boarding an airplane; those with an average body temperature (range 97 – 99°F; 36.1 – 37.2°C) may pass the health control and be allowed to board (CDC, 2020b). Body temperature measurements can also be determined accurately by scanning the wrist of an individual (Chen et al., 2020). One study suggested thermal screening was useful in general to analyze imported cases of COVID-19 in Taiwan (Liu et al, 2020). Infrared scanning cameras can be used without being close to a person who might be infected. While operational and performance requirements need to be factored into their use, they can be faster than handheld devices and, if connected to a camera may enable suspected individuals to be flagged for secondary inspection (FDA, 2020). Additionally, such a system can store information for future use, which might enhance track and trace of individuals close to a confirmed COVID-19 case, although important privacy issues would need to be addressed.

Few U.S. airports check body temperatures given the CDC found only nine people positive with COVID-19 out of over 766,000 passengers at 15 funneling airports where international arrivals underwent temperature checks and health attestations (Dollard et al., 2020). Some airports that were considering implementation decided not to move forward given the costs and limited efficacy in reliably identifying individuals with COVID-19. A limited number of U.S. airports deploy infrared or thermal imaging devices to check body temperatures, and some abandoned their use once the pilot testing concluded given their efficacy is sensitive to technique, training, geographic location, bodily location for the scan, disease prevalence, disease natural history, and other factors (Mouchtouri et al., 2020; Pitman et al., 2020).

It is unlikely that body temperature screening for COVID-19 in airport settings will be useful to risk mitigation because:

- The sensitivity of infrared thermometers and scanners to detect fever of any etiology is around 86% (Quilty et al., 2020).
- Only 28 – 34 % of COVID-19 infected individuals develop a fever (Menni et al., 2020; Richardson et al., 2020).
- Some passengers might be in the incubation phase of the disease and will not display any symptoms. The typical incubation period for COVID-19 is considered to be approximately five days (CDC, 2020e), with individuals infectious up to 2.5 days before the onset of symptoms (Wolfel et al., 2020).
- Some travelers might choose to conceal their fever by taking anti-pyretic medications, such as acetaminophen or ibuprofen (Jamerson & Haryadi, 2020).

6.2.2 Low Oxygen Saturation

For most healthy individuals, normal oxygen saturation (SpO2) at sea level ranges from 94 to 100% (Goldberg et al., 2012). At ground level, the average SpO2 of a healthy person is around 97 %, and at cruising altitude (approximately 35,000 to 39,000 feet) it drops to around 93 % (Humphreys et al., 2005). Of course, if low SpO2 is suspected the individual should receive attention by a physician, immediately. Low SpO2 can manifest as a symptom of COVID-19 (CDC, 2020d; Wadman, 2020; Xie et al., 2020). SpO2 can be measured using a pulse oximeter, a simple device that clips onto a finger or other body part to measure oxygen levels in the blood. If a finger is used, the nail should be free of polish or varnish as this can lead to false low readings. As such, use of such a device may not be practicable in an airport setting, as passengers could not be required to remove their polish. In addition to questions about the practicability of having pulse oximeters widely available at airports and potentially creating additional points of congestion of passengers when using such a method, the effectiveness of the method should be considered. The potential screening effectiveness for COVID-19 through oxygen saturation measurement is likely to be less than 20% for infected people who have mild or medium symptoms (Wu & McGoogan, 2020). Further, COVID-19 cases that do not result in arterial oxygen desaturation would not be detected.

6.2.3 Decreased Sense of Taste and Smell

A decreased sense of taste and smell are often reported by COVID-19 cases. A study using a well-validated 40 odorant test in 60 confirmed COVID-19 in-patients and 60 control individuals found that 98% of infected people (59/60) had some olfactory dysfunction, but only 58% had total to severe loss of smell (Moein et al., 2020). Although these results are promising and could lead to a moderately effective screening method, the olfactory test is unfeasible at this time given how long it would take to complete the 40-odorant test. There is no commercial screening method based on this principle currently available.

6.3 INNOVATIVE COVID-19 DETECTION SUPPORT METHODS UNDERGOING RESEARCH TESTING

6.3.1 Canine Coronavirus Surveillance

There are ongoing efforts to establish medical detection protocols for SARS-CoV-2, and to train and assess the effectiveness of the use of sniffer dogs to screen people for COVID-19. Canine sensing is being explored in some airport settings with dogs trained to detect volatile organic compounds produced by COVID-19 through the odor from sweat, tracheobronchial secretions, urine or saliva (Giordano, 2020; Jendrny et al., 2020; Smithsonian, 2020). Preliminary studies reported by Bielecki et al. (2020) show that dogs trained in COVID-19 detection protocols and used at the Helsinki airport could detect SARS-CoV-2 in travelers with “satisfying results” and a “sensitivity of almost 100 %”. A proof-of-concept study used 18 detection dogs with training experience in explosives, search and rescue, and colon cancer detection, and concluded that the odor of COVID-19 positive persons is different and can be detected by trained dogs (Grandjean et al., 2020). The dog training methods are similar to those used for other sniffer dog training, albeit the disease scent (University of Helsinki, 2020a) and training are more complex (see Figure 6.1).

In a randomized, double-blind controlled study with eight detection dogs trained for one week to detect saliva or tracheobronchial secretions of SARS-CoV-2 infected patients, dogs correctly identified samples from hospitalized and clinically diseased COVID-19 patients with a sensitivity of 82.6% and identified non-infected individuals 96.4% of the time. Out of 1,012 randomized samples, dogs averaged a detection rate of 93.7% with 949 correct identifications of the presence/absence of disease (Jendrny et al., 2020). These results led some airports to pilot canine sensing (Dubai, 2020; Machemer, 2020). The United Arab Emirates (Emirates News Agency, 2020) is already using dogs to screen travelers arriving at the Dubai Airport, and have extended the pilot study to include airports in Abu Dhabi and other cities.

Key observations

- Canine surveillance could offer a non-invasive, fast, and effective COVID-19 diagnostic tool.
- Safety: Would not expect direct contact of passengers with the dogs, detection is done at a special sniffing station.
- Early detection: Dogs can detect COVID-19 infection even at early stages, and on asymptomatic persons.
    - The time it takes a dog to learn the virus odor ranges according to their sniffing working experience.
    - It is estimated that one dog might be able to screen up to 250 people per hour.
- Initial studies suggest effectiveness above 90%, which is above the WHO's standards for a diagnostic test.
    - Dubai's Ministry of Interior said their dogs achieve 92% accuracy.
    - Trials in Corsica achieved 95% accuracy.
    - 100% achieved at a pilot from the University of Helsinki.
- Samples are taken from sweat, saliva or impression smears:
    - Samples from sweat in armpits (Dubai Airport) in a swab.
    - A 1-week trained detection dogs detected the virus from saliva or respiratory secretions.
    - Impression smears to arms and neck skin (Helsinki Airport)
- Training: COVID-19 detection dog training takes around 8-10 weeks.
- Cost and availability of canines and handlers: Undetermined at this time.

Figure 6.1 Sniffing Station and Bio-detection Dog in Training. Source: LSHTM, 2020.

Figure 6.2 Canine coronavirus detection-screening station at Helsinki-Vantaa Airport. Source: Screenshot from video, University of Helsinki (2020b)

In order to identify SARS-CoV-2 positive cases, dogs need a much smaller sample of 10 to 100 molecules, compared with 18,000,000 molecules for RT-PCR tests (Finavia, 2020) and take less time to identify an infected person. A scheme starting with four sniffer dogs at Helsinki-Vantaa Airport in Finland (see Figure 6.2) has been able to detect the presence of the virus in less than 10 seconds with nearly 100% accuracy (Finavia, 2020). The pilot study is currently on a voluntary basis and is available for all passengers and airport personnel (City of Vantaa, 2020).

Limitations of the canine detection method include passenger screening time and the screening capacity of 50 person/dog/hour. This would require large-scale dog training efforts (in the range of 50 to 100 dogs for a major transportation hub) and accompanying personnel training (Machemer, 2020). Further research is needed for canine coronavirus detection to identify, with certainty, the scent combination dogs are picking up when detecting a COVID-19 infection. Pilot studies are looking into how to improve the training, safety, and protocols, such as knowing which samples are best suited to dogs, whether from the impression smear samples, sweat from the forearm or neck, saliva, or whether sniffing masks would be sufficient (University of Helsinki, 2020a).

Canine detection screening may be significantly more efficient than laboratory diagnostic tests, but also potentially much more expensive. The cost and availability of dogs and handlers are important variables. Breed is also important, and there are shortages worldwide of appropriate dogs for use as working sniffer dogs. Additionally, though training could be done in 8 – 10 weeks, identifying and procuring dogs could take much longer. Dogs also have very strict limitations on hours worked before rest periods and limitations on work environment to ensure the dog's health and the efficacy of scent detection. In the Helsinki study, dogs were one-hour on, two-hours off over a day shift. There are also many variables in a busy airport environment that affect a dog's ability to detect the trained scent reliably.

6.3.2 Artificial intelligence Cough Test

A promising research avenue being explored is the use of artificial intelligence (AI) to compare the coughs, spoken words (in different languages), and respiration patterns of COVID-19 infected people with those of healthy people (Brown et al., 2020; Laguarta et al., 2020; Mishra et al., 2020; Stebbing et al., 2020; Vijayakumar & Sneha, 2021). Small differences in the way healthy and infected people cough have been detected (Laguarta et al., 2020). However, for SARS-CoV-2, coughing develops later in the infectious period, if at all, and these subtle differences are not noticeable to humans.

Using deep learning systems, the model was ‘trained’ by analyzing coughs from 4,256 volunteers; 1,064 subjects were used to check the system's accuracy (Figure 6.3). The system uses smartphones, tablets, smartwatches, and computers to collect recordings about forced coughs and invited the user to select a language (currently offering English, Spanish, and Catalan). The user recorded a forced cough and indicated his/her country of origin, age, the presence of any COVID-19 symptoms, any previous knowledge of being infected, any information about official testing or doctor assessment, and the days since the last test (MIT, 2020).

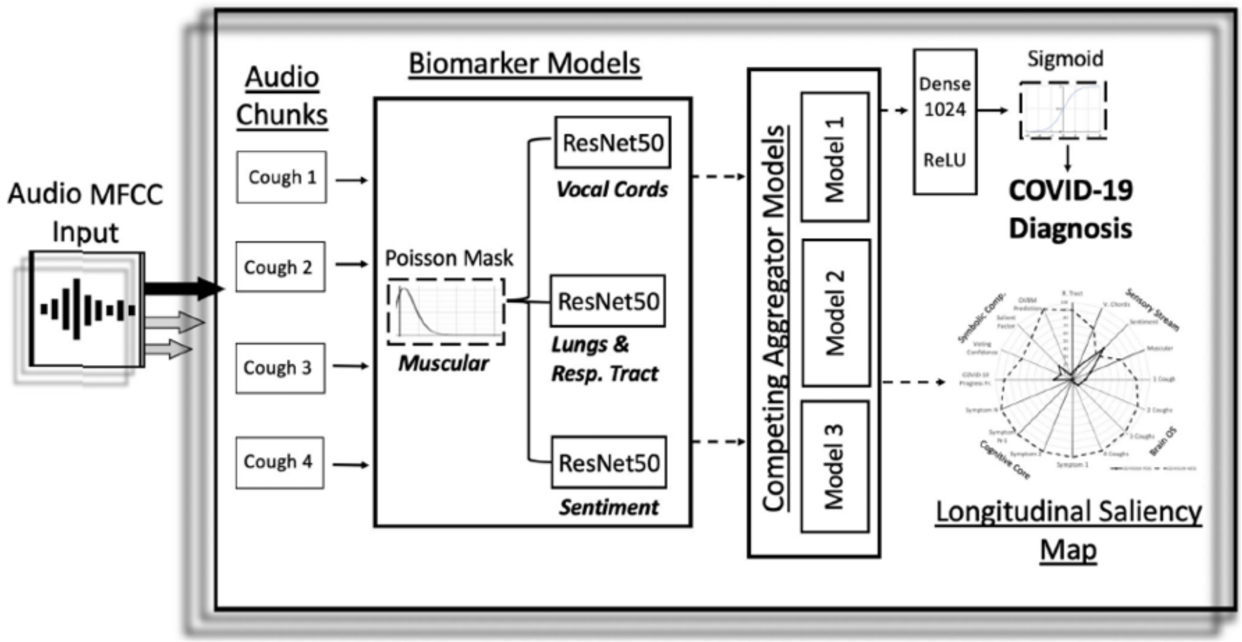

Figure 6.3 Architecture of the COVID-19 discriminator with cough recordings as input and COVID-19 diagnosis and longitudinal saliency map as output (Laguarta et al., 2020)

The sensitivity of the AI system was reported to be 98.5% in identifying coughs from people who were confirmed to have COVID-19, importantly, including 100% of asymptomatic infected people (Laguarta et al., 2020). Data collection has continued since May 2020 by using the COVID-19 screening test application (https://opensigma.mit.edu/). Up to November 2020, some 70,000 recordings of forced-coughs have been collected, with 2,680 confirmed to have COVID-19 (Scudellari, 2020). U.S. Food and Drug Administration (FDA) approval to incorporate this model into a smartphone application (app) is being sought as this might allow large-scale, low/no-cost, convenient, and non-invasive prescreening (Chu, 2020). This application is not yet available, but if found effective and approved by the FDA, it could be deployed directly. This prescreening test could be included as part of the self-assessment for symptoms for those with smartphones who check-in online for a trip or as a daily screening requirement for airport employees.

Similar research projects to detect COVID-19 through cough analysis are being developed by the Bill and Melinda Gates Foundation, the ‘Cough against COVID’ by the Wadhwani Institute for Artificial Intelligence in India, the ‘Coughvid’ project at the École Polytechnique Fédérale de Lausanne in Switzerland, and the ‘COVID-19 Sounds’ project (https://www.covid-19-sounds.org/en/) at the University of Cambridge (Scudellari, 2020).

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7.0 NPI LAYERING: PHYSICAL ENGINEERING CONTROLS, VENTILATION AND RISK MODELING

Commercial airports are designed to advance passengers efficiently through a series of activities in support of their journey. No matter the airport, departure and arrival processes are similar (see Figure 7.1). However, airports differ substantially in their architectural form, size, layout, wayfinding, use of trains, trams and buses, and food, beverage and concession offerings.

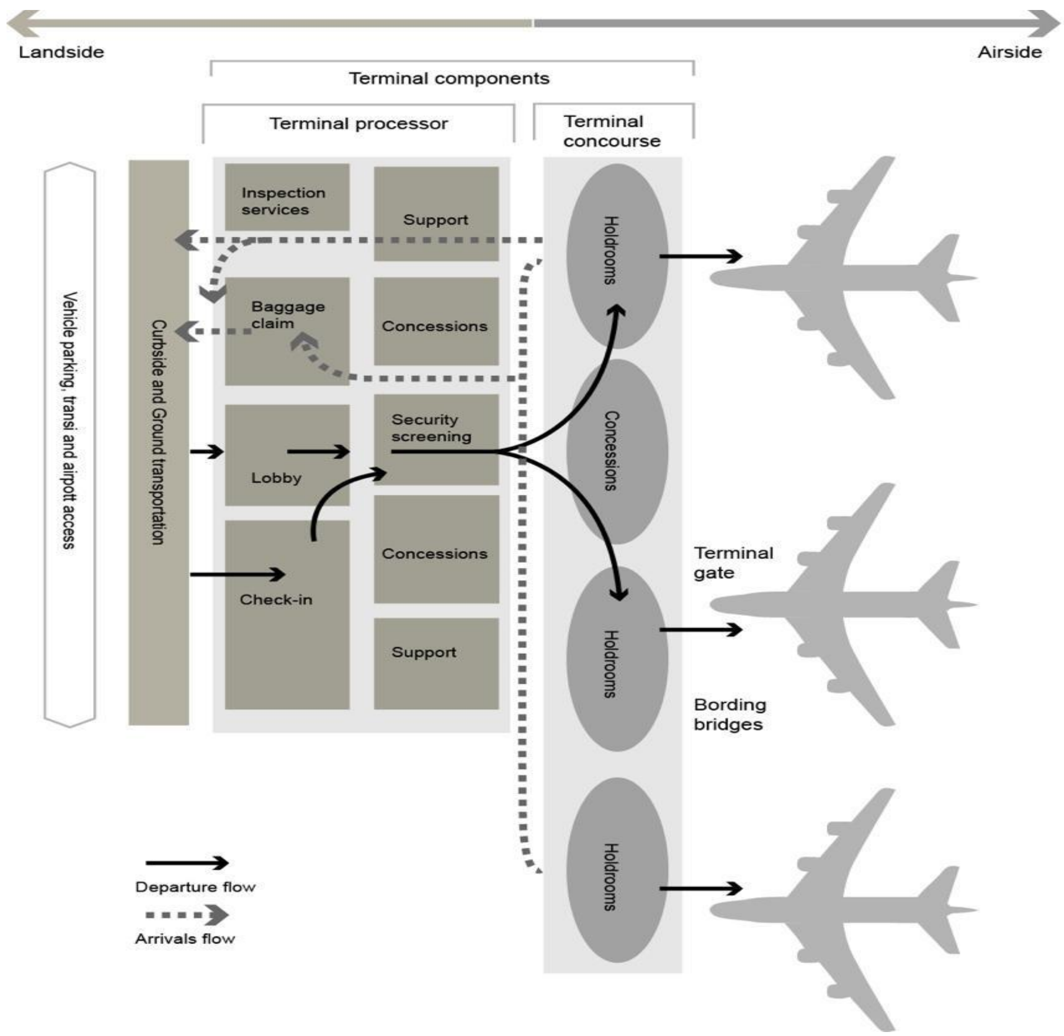

Figure 7.1 Schematic of the components of an airport terminal; intra-airport transportation not shown. (Adapted from FAA, 2018)

In temperate climates, some airport terminal functional spaces take advantage of passive or open-air ventilation. However, the majority of terminal buildings have mechanical systems that provide ventilation and thermal comfort. The design and operation of an airport's mechanical ventilation system is complex, accommodating changing occupant densities, daylighting, and glazed facades. Heating, ventilation, and air conditioning (HVAC) systems maintain thermal comfort and adjust to variable heat gains and losses on a daily and seasonal basis. Such systems draw in outside air and mix it with a portion of recirculated air before passing it through filters to remove a portion of particulate matter carried by the air streams. In areas where aircraft and ground equipment emissions are present, these systems may use carbon or other adsorbent media filters to remove odors and/or contaminants from the outdoor air.

Basic design and operation of HVAC systems in airport terminal building are described in this chapter, with a discussion of demand-controlled ventilation. This is where thermal, occupancy or carbon dioxide (CO_2) sensors may be used to signal increased numbers of occupants and/or thermal load that require a temporary increase in air supply. **Given the airborne transmission route of the SARS-CoV-2 virus and the COVID-19 pandemic, airport ventilation systems can be adapted to help reduce transmission risks.** To do so, building management systems (e.g., central processing, sensors, and controls) might require additional evaluation by knowledgeable mechanical engineers and contractors, so that they can accommodate the unique requirements of mitigation for SARS-CoV-2.

As passenger numbers begin to recover, physical distancing at many airports to the recommended 6 feet (1.83 meters) may be difficult to accomplish in certain areas. Choke points for passengers include at the gate area waiting to board, especially when an arriving airplane disembarks into a crowded waiting area, or when queues develop at check-in, security, customs and immigration checks, and around baggage claim devices. Even with passenger volume at 40% of pre-COVID travel, the increased space required to accommodate physically distanced queues can result in congestion within some terminals. While physical distancing and facial coverings/ face masks help reduce the risk of transmission, there are times in a terminal, an airport bus or train when the distance between passengers may be less than recommended. Even with a suitable facial covering worn properly, a portion of exhaled breath or inhaled air is likely to by-pass the mask. Therefore, ventilation systems, as one of several layers of risk mitigation, serve an important function in compensating for these typical airport conditions. The amount, direction, and turbulence of the surrounding airflow determines how rapidly a plume of exhaled breath will be diluted and dispersed, which translates into its disease mitigation functionality.

Ventilation systems used in airport terminal buildings have typically not been designed to mitigate the airborne spread of respiratory pathogens. Additional functionality may be required to augment the capacities of existing systems when appropriate physical distancing cannot be maintained, and/or there is insufficient mixing, dilution and removal of air in the immediate area. Ventilation influences infectious aerosols inhaled by building occupants. While enhanced ventilation may not completely address infection control in an airport terminal building, increased airflow, directional airflow and filtration can help reduce the risks significantly. Good engineering practices that help reduce airborne exposures are informed by the latest industry standards for HVAC systems (ASHRAE, 2020); many airports adjusted their HVAC operation in accordance with the ASHRAE guidance. The role of ventilation in airport operations is discussed in detail in section 7.2 of this report. Using properly sized portable air cleaners, and/or installing upper room ultra violet (UV)-C lamps, increases the effective air exchange rates. Models presented in this chapter simulate the transmission risk for several typical airport scenarios and include an analysis of the effectiveness of the ventilation strategies mentioned here.

Data from the interviews and questionnaires conducted for this report (see Chapter 3) revealed that some airport operators considered installing 'disinfection' devices in air ducts. **Given the lack of evidence that SARS-CoV-2 is transmitted through mechanical ventilation systems, the installation of any additional disinfection devices in the air duct system it is likely to be unnecessary.** In any event, such devices would be redundant to implementing enhanced filtration provided it was to a standard that removed virus-carrying particles. The survey data also showed that some airport operators were erecting plexiglass barriers (see Figure 7.2) to separate passenger lines during security screening. Such barriers could create 'canyons', blocking airflow and inhibiting mixing, dilution, and removal of exhaled particles, and thereby potentially increase viral transmission risk. Passengers following an infectious person shedding viruses might encounter higher concentrations as they progress in line, due to reduced dilution. As such, additional modeling studies were undertaken to assess the implications of restricted airflow under these conditions. Additional analysis to develop an optimized set of design dimensions would be necessary to make specific recommendations.

Figure 7.2 Physical barriers in queue lines in well-ventilated areas with high ceilings (Courtesy of Lavi industries).

7.1 AIRPORT OPERATIONS AND DESIGN OF VENTILATION SYSTEMS: ASHRAE, ACRP AND OTHER GUIDELINES

An airport terminal is a complex interface between passengers, aircraft, commercial concerns and modes of ground transportation. It includes three key components: the terminal building(s), airside facilities, and landside services (see Figure 7.1). The interface between landside and airside occurs in the terminal building and includes the spaces in the terminal 'processor' where passengers traverse check-in and security screening. It also includes the terminal 'concourse' where the hold rooms, or boarding gates, and the majority of concessions are located. The airside facilities comprise the areas restricted to aircraft operations on the apron, such as maneuvering requirements, aircraft parking, servicing, and maintenance, and include the concourse areas inside the terminal. The landside facilities connect the airport terminal to ground transportation systems, which include the curbs, staging, parking, and roadways. This Curb-to-Curb report does not extend beyond the curb at landside.

Airport planning and design must meet the evolving requirements of the commercial aviation industry as well as its commercial activities, environmental considerations, and local factors; the Airport Cooperative Research Program (ACRP) under the U.S. Transportation Research Board (National Academies of Sciences, Engineering, and Medicine, 2010) describes these. During this COVID-19 pandemic, one of the key challenges facing airport operators is protecting the health of passengers and personnel. With many constraints and regulations governing airport building design, terminal size and layout may constrain physical distancing requirements necessary to help reduce SARS-CoV-2 transmission. For this reason, the layered approach is particularly relevant to aviation facilities.

7.1.1 Design of Airport HVAC Systems

The local mechanical code and standards from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) influence the design of an airport terminal building's HVAC system. Generally, most planning and design guidance includes consideration of engineered ventilation systems to bring in appropriate amounts of fresh air, increase airflow (air changes per hour; ACH), eliminate any odors or contaminants, and provide thermal comfort. Other planning considerations include incorporating HVAC system redundancies or back up, as sensitive electronic equipment is vulnerable to overheating and may become damaged or inoperative if temperatures fall out of prescribed ranges (National Academies of Sciences, Engineering, and Medicine, 2010). Terminal spaces may have specific requirements for particular locations, for example, design guidance recommends the HVAC system serving security-screening areas include more airflow and air quality monitoring to maintain comfort and minimize odors.

Local mechanical code requirements are also concerned with the security and protection of the HVAC system. For example, they regulate the location and accessibility of air intakes, including recirculation air grills, mechanical rooms, and plenums. These are particularly sensitive in airports as security measures demand restricted access. It is also important to have the capacity to isolate airflow, in the event of a non-conventional chemical, biological, or radiological terrorist attack. For this reason, video surveillance may also be a requirement at the entry points of the HVAC system. Mechanical codes also include provisions for HVAC systems to have effective air filtration or air cleaning systems. In addition, the air intake should avoid drawing in emissions from aircraft fueling and combustion activities at the apron level. Air intakes are usually placed in upper levels in order to draw in cleaner outdoor air.

Ventilation plays an important role in the energy consumption of an airport terminal, as large spaces need large supplies of conditioned air, particularly for spaces experiencing peak occupancy. Therefore, the design of HVAC systems in terminals requires ventilation systems that ensure high quality conditioned air, while saving energy. Mechanical and building codes include provisions for load calculation procedures, minimum ventilation rates, which may be indicated for different types of spaces in terminals, and other standards. In general, most codes reference the ASHRAE Standard 62.1 for ventilation and indoor air quality (IAQ), as it outlines minimum ventilation rates, procedures and other measures intended to provide IAQ acceptable to human occupants and designed to minimize adverse health effects (ANSI/ASHRAE, 2019).

In order to determine the load requirements for heating and cooling airport terminal spaces, the building or mechanical codes provide protocols and minimum standards that the HVAC design must follow. In the case of heating airport terminal buildings, recommended minimum temperatures for different types of space types are listed in the code or referenced to ASHRAE standards. For thermal comfort and energy efficiency, most codes reference the standards ASHRAE 55 - Thermal Environmental Conditions for Human Occupancy, and ASHRAE 90.1 - Energy Standard for Buildings Except Low-Rise Residential Buildings (ANSI/ASHRAE, 2017; ANSI/ASHRAE/IES, 2019). Air filtration for HVAC systems needs to follow requirements and recommendations found in relevant codes. Most of the available guidance on filtration has been provided by ASHRAE, which has been leading efforts in research, testing, and standardization of filtration and air cleaning (ANSI/ASHRAE, 2017a). The purpose of filtration is to reduce exposure to contaminants by removing them from the ventilation and recirculated air, thereby avoiding distribution of any harmful pollutants. **Of most concern for airport terminal HVAC systems during the COVID-19 pandemic are bio-aerosols, more specifically those aerosols that may harbor SARS-CoV-2 that can be present in a broad distribution of particle sizes.**

ASHRAE (2016) guidance indicates that HVAC systems can help control indoor bio-aerosols through a combination of appropriate ventilation and filtration, and recommends several ventilation rates and higher efficiency filters. The selection and maintenance criteria of filters and air cleaners depend on the type of contaminants, sizes and concentrations, requirements of air cleanliness levels, and space available to install and access the equipment. There are three main operating characteristics of air filters and cleaners that affect the capacity of HVAC systems to remove infectious aerosols from airport indoor environments: efficiency of removal (by particle size), airflow resistance, and life-cycle cost; this is discussed in section 7.2. The air distribution design is also regulated by mechanical and building codes and ASHRAE standards (ASHRAE, 2017; ANSI/ASHRAE, 2019). Several requirements may apply to ductwork, such as air ceiling plenum restrictions to meet any air quality, acoustical, and fire protection requirements.

The selection of HVAC equipment is also part of the design process, as capacity, safety, installation, and maintenance must be suitable to the terminal spaces and facility management. HVAC design can include climate change resilience considerations that may be oriented towards flood protection, system redundancy, and structural resilience. Adding redundancy to the HVAC system is another resilience consideration. As a critical facility, the HVAC design for an airport can include redundancies of at least N+1, where N is the baseline capacity, to continue operating in the event of failure of a component. Designing structural resiliency in an airport HVAC system seeks to ensure that the mechanical equipment can withstand structural risks, like earthquakes and wind loads.

7.2 MECHANICAL AIR HANDLING SYSTEMS FOR AIRPORT TERMINALS

The efficient cooling of large airport terminal spaces requires a combination of mechanisms. Current energy codes tend to favor HVAC system controls that use a variable air volume (VAV) strategy. Glazed areas are mostly shaded from direct solar gain with glass of appropriate thickness and low emissivity (e). Glazing is heated locally by hydronic heat when the outdoor temperature is less than the internal temperature conditions. In recent years, better building envelope details and improved lighting technologies have diminished the cooling load in many types of space. In most areas within airport terminals, occupants create the predominant requirement for the cooling load, and their presence or absence will strongly influence the total HVAC airflow rate to the occupied space.

In the VAV HVAC strategy, air handling units (AHUs) mix outdoor air with return air, filter the mixed air (now called ‘supply air’), and cool and dehumidify it for distribution to multiple thermal control zones in the building. The air ducted to each zone’s regulating box varies the flow of supply air to each space based on the dry-bulb temperature in the respective zone. Heating and cooling requirements in a zone are therefore the result of heat transfer through the building envelope, internal heat generated by lighting, equipment, occupants, air infiltration from outdoors and direct solar gain through glazing.

As thermal loads increase in a zone, due to solar gain or higher occupant density, the zone's dry bulb temperature will rise and the local VAV controller will increase flow to compensate. Likewise, when the temperature falls the flow will decrease. Most VAV controllers have a minimal flow setting. At minimum flow, VAV controllers not equipped with a reheat option will tend to overcool the zone. If the zone is equipped with reheat, the heating coil or element will be activated with minimum flow to heat the zone. Controlling the temperature in the space assures that the amount of heat added or subtracted by the HVAC system equals the net inflow of thermal energy for people. Figure 7.3 depicts the VAV HVAC strategy schematically.

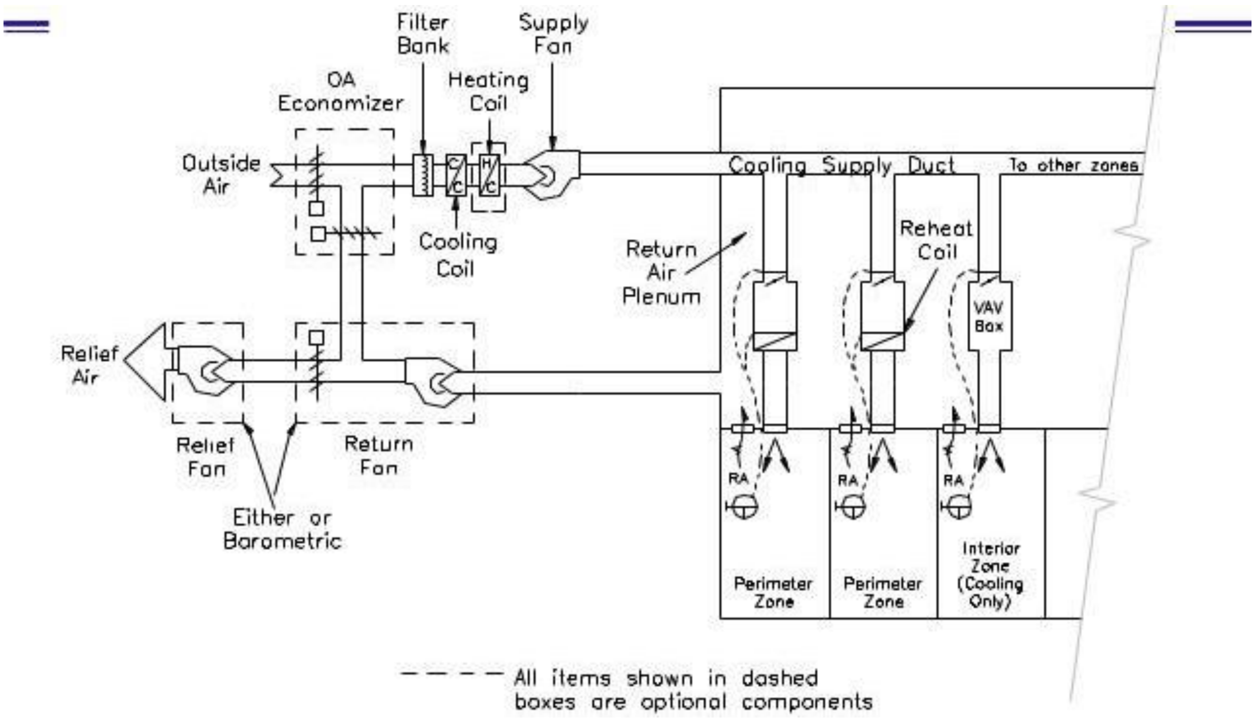

Figure 7.3 Schematic depiction of the VAV HVAC Strategy. The AHU mixes outdoor and return air, filters, cools and dehumidifies, heats, and supplies to local VAV control zones. The local control zone's VAV box regulates the airflow to the zone to regulate temperature in the space. (Extracted from Reinhard, S., Gottshall, T., Hydeman, M. Slideshow for X472 HVAC System Design Considerations, University of California Berkeley Extension, Fall 2015.)

In most cases, HVAC supply air is delivered at a temperature of approximately 51-54°F (10.5-12.2°C). This temperature assures that even when outdoor conditions are humid, humidity in the space is less than 60% relative humidity (RH) with a space temperature of 74°F (23.3°C). Air supplied to a perimeter zone may be reheated to offset heat loss from envelope elements such as glazing. Alternatively, perimeter areas may control heat loss from glazing elements using fin tube convectors at floor level or radiant panels mounted in the ceiling. Using Dedicated Outdoor Air Systems (DOAS) in combination with hydronic heating and cooling may be an attractive design strategy in some cases. This decouples the heating and cooling of the space from the conditioning of outdoor air required to meet ventilation requirements. While effective for reducing energy use, it may forego the ability to improve air filtration or increase outdoor air delivery during an economizer operation that conventional mixed air space conditioning strategies provide. As such, its role in meeting airflow demand during a pandemic crisis must be carefully evaluated by knowledgeable professionals.

The supply of outdoor air is regulated by building codes (ANSI/ASHRAE, 2019). Most building designs assure that sufficient outdoor air is supplied to make up for air exhausted from the space, plus any additional outdoor air to pressurize the building. In many climates, airside economizer cycles, where temperate outdoor air is brought into the building for cooling purposes (also called 'free cooling'), will override the minimum outdoor air requirements when unconditioned outdoor air can be mixed with return air to provide appropriate supply air conditions to minimize energy expenditure for cooling. Consequently, during some weather conditions the supply of air may be 100% outdoor air.

7.2.1 Demand Control Strategies

In some airport terminals, demand-controlled ventilation (DCV) systems are installed. DCV systems measure occupant-generated CO_2 in an attempt to vary the amount of outdoor air provided to the space based on the actual occupancy and minimize the cost to ventilate intermittently high occupancy spaces. As CO_2 concentrations in the space increase above a set point, the outdoor airflow is automatically increased. Likewise, when CO_2 concentrations in the space decrease, the outdoor air volume is decreased. In general, the minimum outdoor air requirement in most jurisdictions require a minimum flow based on the floor area served. Additionally, to minimize air infiltrating the building through unfiltered and unconditioned pathways, the minimum outdoor airflow to the space should compensate for all air that is exhausted. An additional margin of supply air can be prescribed to ensure pressurization of the building under all occupied operating conditions.

7.2.2 Filtration Effectiveness

The filters typically found in HVAC systems in airport terminal buildings are located after the outdoor air is mixed with return air. Such filters were originally installed to minimize the fouling of the heat transfer surfaces in the equipment and were generally very inefficient at removing particles in the 1 µm size range. Increased awareness of indoor air quality in the last 20 years has resulted in better quality filters (i.e., higher efficiency of particles removal) being installed in these systems. ANSI/ASHRAE Standard 52.2-1999 define the Minimum Efficiency Reporting Value (MERV) for filters that specify removal efficiency based on particle size (ANSI/ASHRAE, 2017a). The original filters installed to minimize equipment fouling typically correspond to a MERV 6 rating that has no reliable efficacy for removing particles sized 1 µm and below. The filtration of smaller particles increases as the MERV value increases. As filtration efficiency increases, the percentage of smaller particles, including viruses, removed by the systems' recirculated air system will increase. That is, the filtration efficiency of recirculated air is increased, and the clean air delivery rate (for particulate matter) will be increased proportionally. The amount of clean (particle free) air per person is equivalent to the amount of outdoor air per person and the filtration efficiency times the flow of recirculated air per person. In equation form:

$$\text{Clean Air (cfm/person)} = \text{OA cfm/person} + \text{Filter Eff} * \text{RA cfm/person}$$

Where cfm is the airflow in cubic feet per minute; OA is outdoor air; RA is recirculated air; Filter Eff is filter efficiency.

For example, in an airport waiting area, increasing the filtration from MERV 6 to MERV 13 will increase the filtration efficiency from 0 to 90% for 1-3 µm sized particles. Consider a boarding gate area designed for 38 persons per 1,000 ft^2 with a total supply airflow rate of 0.8 cfm/ft^2. Complying with ASHRAE design recommendations of 7.5 cfm of outdoor air per person, plus 0.06 cfm/ ft^2, there would be 348 cfm of outdoor air delivered with the remaining 451 cfm of air recirculating through the system. Increasing the filtration efficiency of the recirculation air to 90% results in an additional 406 cfm of clean air for 38 persons (or 10.7 cfm/person) for a total of 19.8 cfm/person. In many systems, MERV 13 or 14 may be feasible as filters are available within pressure drops that many AHUs can tolerate. Although the SARS-CoV-2 virion is approximately 0.1 µm in diameter (Bar-On et al., 2020), a more relevant dimension has to do with the droplet size of the expired air where the virions are incorporated under normal breathing and speaking as well as during coughing and speaking. Morawska and colleagues found multiple modes of exhaled aerosol droplets, below 0.8 µm, 1.8 µm, 3.5 µm and 5.0 µm (Moreawska et al., 2009). The relative magnitude of associated concentrations were highest for the <0.8 µm fraction but shifted to larger sizes based on sustained vocalization, but still not reaching the concentrations for the <0.8 µm fraction. An analysis regarding viral load in mucous aerosols indicated that the probability of having an infectious virion in a particle less than 1 µm diameter is approximately 0.01 % (Anand & Mayya, 2020). Therefore, MERV 13 would be nearly as effective as using 100% outdoor air, and in many climates much less expensive than cooling and dehumidifying additional outdoor air.

AHUs in some airport terminals may be equipped with filters to adsorb and neutralize intermittent entrainment of emissions from aircraft and ground support equipment on the apron. These filters may include carbon and other adsorption media and may be impregnated with potassium permanganate ($KMnO_4$) or other oxidizing coatings to neutralize odors. The efficacy of these filters for removing particles may be an improvement over MERV 6 filters, but this is highly dependent on the design of the adsorption filters and is not well characterized.

In some cases, pre-filters are incorporated into the HVAC design, installed in locations upstream of higher efficiency filters that may have a higher MERV rating. It is recommended that pre-filters be used to protect filters of MERV 16 and greater (ASHRAE, 2016). A MERV 3 pre-filter is typically at least 20% efficient in removing particles between 3.0 and 10.0 µm in size. A MERV 6 is more commonly used, and provides between 35 and 50% removal for that size range (ASHRAE, 2016).

Operational changes to HVAC systems that should be considered to minimize SARS-CoV-2 exposure risk in airport terminals include:

1) Installing MERV 13 or MERV 14 filtration in the HVAC systems.

2) Reviewing the MERV ratings for any high MERV-rated filter currently in use. Some filters are MERV-rated with an electrostatic charge on the filter. As the charge dissipates, its performance may decrease materially resulting in a filter that had a high rating when installed but that has degraded over time. For example, a filter rated with a MERV 13 when charged will degrade to a MERV 9 as the charge dissipates. (Note: Filters designated as MERV-A rated filters have had any electrostatic charge dissipated prior to testing, so that the MERV rating should not degrade as the static charge dissipates.)

3) Examining options to maximize airflow through the HVAC systems. Depending on the systems installed these actions may include:
   a. During weather conditions that do not require dehumidification (i.e., dew point < 51°F/10.5°C) the supply air temperature set-point in AHU's can be raised to increase airflow to the occupied space.
   b. Delaying lighting upgrades. Maximize lighting operations to increase heat load and maximize airflow. This will adversely affect energy conservation measures, but this may be acceptable during the exceptional circumstances of the pandemic.
   c. Reprogramming the minimum flow for local VAV zones. Those not equipped with reheat may overcool the space during times when occupancies are low. The VAV zones that include terminal reheat will use more energy to control space temperature, but the increased airflow will minimize the risk of encountering infectious doses of SARS-CoV-2.

4) Resetting and commissioning the outdoor air economizer cycle to maximize the use of outdoor air (see section 7.2.3). Minimum flow rates can be set to ensure a building is pressurized under all operating conditions and meets code requirements.

5) If a DCV strategy based on CO_2 concentrations is being used, the 'trigger' space concentration can be reset to increase outdoor air ventilation to the extent practicable.

7.2.3 Commissioning of Airport Terminals and Associated Facilities

ASHRAE published its original guidance document for commissioning HVAC systems in 1989 (ASHRAE, 1989). A number of position papers and guides have emerged since then to describe the value, benefits, and rationale for verifying and documenting that all building systems are appropriately functioning via an effective commissioning process. ASHRAE's Standard 202-2018 'Commissioning Process for Buildings and Systems' (ASHRAE, 2018) and Guideline 0-2019 'The Commissioning Process' (ASHRAE, 2019) are intended to help building owners and designers verify that each facility and its systems meet the owner's project objectives. This type of detailed specification of building systems is critically important and especially so during the COVID-19 pandemic in high use, variable occupancy areas such as airport terminals and their commercial adjacencies. The National Academy of Sciences issued a commissioning guide specifically for airport terminals (NAS, 2015) given the unique and complex nature of the facilities (National Academies of Sciences, Engineering, and Medicine, 2010a).

'Commissioning' as used in this context is defined as the systematic, documented, and collaborative process used to assess the ability of a building and its component systems to meet the design intent and the needs of its occupants (ASHRAE, 2019). It relies on the commitment of the owner/facility manager, contractors, and commissioning agent to ensure success. The term was originally derived from a naval process that was put in place to verify performance of the multitude of critical systems on warships before they went to sea. Now, building commissioning is intended to reflect the systems assessment for the critical equipment operations in new buildings before they are fully occupied or put into service by the owner (McCarthy & Dykens, 2000). What differentiates commissioning from equipment performance verification testing is that it is designed to assess the performance of the entire building as a system and the interaction of various system components. Equipment performance verification focuses on verifying the performance of individual components. Properly executed, the commissioning process includes the training of operating staff and ensures thorough documented verification that all installed systems are performing directly in accord with the design intent and the owner's operational needs (PECI, 1996).

Modifications of the commissioning process can be used to recommission existing buildings to either improve overall performance of the existing system by returning it to its optimal design performance or, as seen during the pandemic response, to ensure the effective performance of new supplementary systems or components that are being installed to help meet specific needs. The various approaches are described as:

- Recommissioning, which generally involves bringing a system back to its original design performance.

- Retrocommissioning, which often involves an energy analysis where existing systems are optimized to achieve better overall performance while meeting the current needs of its occupants.
- Pandemic-Commissioning, which is a specialized function that goes beyond the performance of the system and includes minimizing risk; it becomes an integral part of a facilities infection control program. While some Pandemic-Commissioning actions may conflict with energy minimization goals, they will be justified in terms of minimizing the risk of infection.

While these approaches share many common elements, the driving forces for undertaking this work and their objectives are very different. Commissioning is critically important during these pandemic times. The goal is to turn over to the facility manager a building that meets the design intent to aid in controlling infectious risk.

7.2.4 Pandemic-Commissioning

Few new airport terminals are being constructed, but existing terminals are being renovated and upgraded and can benefit from retrocomissioning to optimize performance in meeting changing demands. During the COVID-19 pandemic, many buildings, including airport facilities, are being retrofitted with various control and exposure reduction technologies. This section focuses on the system verification programs most appropriate to pandemic-commissioning.

Pandemic-commissioning (Pan-Cx), also referred to as Epidemic Commissioning in Place by ASHRAE (ASHRAE, 2020a), focuses on developing a meaningful definition of design intent and an effective design review, in addition to the functional testing. Developing the design intent as part of pandemic-commissioning is unique because, in addition to the review of a commissioning engineer to address functional performance, it requires an infection control/biosafety review component to clarify what the infection control intent/objective will be; these two elements must be harmonized throughout the program.

Given the consideration that went into designing, specifying, and installing the original mechanical systems serving an airport facility, similar attention will need to be given in making any changes. Evaluation of the airport facility will determine current operating conditions and whether it meets the original design intent or those agreed under previous facility upgrades. Any deficiencies identified can be addressed to ensure compliance with HVAC mitigation strategies. Given that pandemic mitigation strategies may not reflect the long-term operational plan for the facility, they can be considered tactical modifications to minimize risk for building occupants. An experienced engineering commissioning agent who understands the airport’s objectives and the various options being considered should oversee systems evaluation; are presented in ASHRAE 62.1 (2019).

While commissioning may often be viewed as a series of functional performance tests, effective pandemic-commissioning must begin at the programming review phase where the commissioning agent, the design team, the infection control specialist, and facilities manager review the building program and identify the information required for specifying the effective design and performance criteria for building performance. The commissioning agent can also perform a critical function during the design review. This provides an important quality control element for the design team in reviewing and documenting any discrepancies between architectural/HVAC design and specifications in the owner's building system performance criteria.

7.3 EMERGING AIR CLEANING TECHNOLOGIES

As reported in Chapter 3, airport owners and operators are considering installing air disinfection equipment in air ducts or in terminal areas to treat room air. Evidence should be gathered to clarify the potential for of SARS-CoV-2 transmission through air ductwork (i.e., infectious particles distributed from one area of a building to another through ventilation ductwork resulting in infection). To date, a single study describes an outbreak at an apartment building in South Korea where the authors suggested that virus spread through ductwork and led to infections (Hwang et al., 2020). Therefore, when considering employing emerging air cleaning technologies, the limited evidence of transmission through airborne virus spread of SARS-CoV-2 through ductwork should be considered when evaluating the efficacy and cost of in-duct air cleaning technologies. More studies are needed to evaluate other air cleaning technologies that are being promoted by vendors as effective for disinfection. Some technologies can produce harmful emissions, and as a general rule, **any filtration and air-cleaning technology that is known to produce significant amounts of contaminants should not be used. Air cleaning devices considered for an airport's HVAC should be evaluated for any harmful unintentional emissions or byproducts.**

Alternatively, technologies that focus on increasing ventilation rates (and thus more quickly removing and/or diluting airborne particles) or in-room filtration/disinfection (which eliminates airborne infectious virus from a space prior to exposing room occupants) are expected to provide more effective treatment of the air and consequently reduction of airborne transmission. Some airports are adopting a flexible rollout approach, where standalone air cleaning solutions are used as needed. HVAC systems can be supplemented with air cleaning stand-alone units that are mobile and can be deployed as needed in different spaces, such as breakrooms. These technologies are available commercially in different capacities according to room sizes. The following discussion reviews emerging technologies in the context of reducing exposure risk to building occupants to airborne SARS-CoV-2.

The CDC (2020) has recently issued a statement on 'emerging technologies' which in fact are really not new. It is the application of these technologies in air duct and room air disinfection has recently being promoted aggressively as a strategy to mitigate SARS CoV-2 transmission indoors.

7.3.1 Bi-polar Ionization, Corona Discharge, Needlepoint Ionization and other Ion or Reactive Oxygen Air Cleaners

There are a number of technologies that work by using electrical voltage to generate reactive ions. Depending on the technology, the generated ions may be mixtures of reactive oxygen species (ROS), ozone, hydroxyl radicals, and superoxide anions (collectively referred to here as 'ions'). The rationale for generating ions is that they are thought to inactivate biological agents (e.g., viruses), cluster around airborne particles to agglomerate the particles into larger masses that drop out of the air or are filtered out of the air, and breakdown gaseous contaminates such as volatile organic compounds (VOCs). In most cases, the impacts of ions have only been shown in controlled laboratory environments (EPA, 2018). The installation of these devices in AHUs to distribute the ions through the ductwork system and into an occupied space, or positioning a self-contained unit located within critical or high traffic spaces for local disinfection has been proposed. In terms of validated efficacy, ASHRAE states that, "convincing scientifically-rigorous, peer-reviewed studies do not currently exist on this emerging technology" (ASHRAE, 2020b). Beyond efficacy, there are concerns that such technology can potentially produce harmful ozone and/or secondary byproducts (e.g., irritating gaseous compounds and particles generated by chemical reactions). Some of the companies use low enough voltage that does not promote the production of ozone.

7.3.1.1 Dry Hydrogen Peroxide

Dry hydrogen peroxide (DHP) technology (e.g., gaseous hydrogen peroxide) uses ambient humidity and oxygen to catalytically produce gaseous DHP. DHP equipment (either in-duct or portable room size) delivers DHP continuously throughout a space. DHP equipment manufacturers state that the concentration of DHP released into a space at concentrations of five and 25 parts per billion is far below human exposure limits and therefore the technology can be used in occupied spaces (CDC, 2014; Ramirez, et al., 2020; Synexis, 2020). Several small-scale hospital-based peer-reviewed studies suggest that DHP reduces surface bacterial contamination (Chan et al., 2011; Ramirez et al., 2020). Ramirez and colleagues did not detect a significant difference in airborne concentrations of bacteria using DHP technology (Ramirez et al., 2020). **Given the limited efficacy testing of DHP, especially when used as an in-duct product in a non-healthcare setting, it is recommended that there should be a careful review of performance data along with evidence that devices do not produce harmful byproducts (e.g., ozone).** When considering room-sized devices, it is critical to understand the target concentration of DHP and the volume of airflow per time (e.g., cubic feet per minute) through the space to understand whether that concentration of DHP in the air will have any meaningful impact in the space.

7.3.1.2 Ozone Generators

Some companies market devices that intentionally generate ozone to achieve air-cleaning effects. Ozone is a potent lung irritant and has been associated with a number of respiratory symptoms (ASHRAE, 2015; EPA, 2018). Additionally, ozone reacts with chemicals routinely found in indoor air to produce harmful byproducts such as ultrafine particles, formaldehyde, ketones, and organic acids (EPA 2018). Some devices may market that they produce ozone at levels acceptable for health-based standards. However, it is likely that ozone at these levels does not have any air-cleaning effect and yet still may produce harmful byproducts (EPA, 2018). **Due to the overwhelming health concerns, the use of products that intentionally generate ozone is not recommended (ASHRAE, 2015; EPA, 2018).**

7.3.1.3 Hypochlorous Acid (HOCl) Disinfectant

Hypochlorous acid (HOCl) is an active ingredient in a number of EPA registered disinfectants approved for use against SARS-CoV-2 on surfaces (i.e., EPA List N) (EPA, 2020). The mechanism of disinfection involves destroying the cell wall of microorganisms, thereby rendering them inactive (Block & Rowan, 2020). Generally, HOCl-based disinfectants require a contact time of 5-10 minutes for inactivation of SARS-CoV-2 (EPA, 2020). HOCl-based disinfectants can be purchased ready to use or can be synthesized through electrolysis of a saltwater solution (Sarada et al., 2020). Products are sold as sprays for surface wiping or for use in electrostatic sprayer or fogging devices. HOCl-based disinfectants have a good safety profile, **however, when used with sprayer or foggers it is still recommended that they be used only when space is unoccupied and the operator wears appropriate personal protective equipment** (PPE), such as eye protection. If used according to the manufacturer's instructions, HOCl-based disinfectants should be effective at disinfecting surfaces.

7.3.1.4 Germicidal Ultraviolet (GUV) Air Disinfection Technologies

Germicidal ultraviolet (GUV) is a well-established technology for decontamination of air, water, and surfaces. Although it is most widely used for water safety, it is increasingly used for surfaces and has a long history as a highly efficient way to disinfect large volumes of room air. It is also used in ventilation ducts to reduce mold growth on coils, mitigating sick building syndrome, and to decontaminate recirculated air. It can be used alone or with high-efficiency filters in portable room air cleaners as another approach to supplementing ventilation, whether natural or mechanical. It is easier to incorporate this technology into new HVAC systems. It can be difficult and cost prohibitive to retrofit systems for in-duct applications to work effectively given the exposure time needed to kill viruses, with the constraints of high airflow rates and short ductwork length.

While 254 nm GUV can be generated efficiently by mercury (Hg) vapor lamps, similar to fluorescent lamps used for lighting, COVID-19 has accelerated the development of two advances in GUV (UV-C) technology: LED UV sources with a wavelength of 255-280 nm) and Far UV, most commonly 222 nm. Longer wavelength UV is also promoted for air and surface decontamination, but its germicidal effect is too slow to be of practical use in mitigating SARS-CoV-2 transmission. UV portals intended to decontaminate people's clothing and exposed skin while walking through an irradiated space is another potential application, although efficacy is unproven in this context. Trials have also been set up in several airports for security check trays returns.

As with other technologies, the COVID-19 pandemic has spawned a variety of applications that are unproven, theoretically unsound, and possibly dangerous, but that are being marketed aggressively as solutions to airport operators and airline companies as safe and effective. **As such, those applications that may be of use in an airport setting are summarized. The following summary recommends which of the following applications, or combination of applications should be considered for use in airport terminal buildings.**

- ***Upper room GUV – both 254 nm Hg lamp sources and LED 255-280 nm sources.***

In 1942, Wells and Wilder demonstrated in schools outside of Philadelphia that upper room Hg lamps could mitigate transmission of measles – the most infectious airborne virus known (Wells & Wilder, 1942). Upper room UV with air mixing was widely used in public spaces before the introduction of antibiotics to treat tuberculosis (TB) and vaccines to prevent the common respiratory viruses of childhood namely, measles, rubella, and chicken pox. With the TB resurgence in the mid-1980s, there was a revival of GUV use in the U.S. in healthcare settings, homeless shelters, and correctional facilities, but interest has fallen with the decline in domestic TB case rates.

Globally, however, upper room GUV can supplement natural ventilation for airborne infection control – of growing importance with global warming as windows are closed for efficient use of ductless air conditioners or because of severe air pollution. All known human pathogens contain nucleic acids and are susceptible to GUV, which works by causing nucleic acid mutations. The SARS-CoV-2 virus, like other coronaviruses such as influenza and vaccinia (Smallpox) are all highly susceptible to relatively low doses of GUV (Walker & Ko, 2007). Upper room GUV is highly efficient because it works by disinfecting large volumes of air above the heads of room occupants. It is dependent on good vertical air mixing from either convection currents in occupied rooms, mechanical ventilation, or mixing fans to achieve high levels of equivalent ventilation in the lower, occupied room. Two carefully controlled field trials produced about 80% protection against human-generated TB, an exclusively airborne infection (Escombe et al., 2009; Mphaphlele et al., 2015). Another documented the upper room GUV dose required to produce the air disinfection equivalent air changes per hour (ACH) equivalent (Eq. ACH) of 24 (Mphaphlele et al., 2015).

UV-C 254-280 nm, does need to be applied carefully since it can cause eye and skin irritation with direct, high intensity exposure (almost always accidental) exceeding well-established workplace exposure limits for UV radiation established by ACGIH (ACGIH, 2020). UV-C upper room lamps can be installed and commissioned to assure lower room exposure that remain well within the threshold limit value (TLV) and ensure that there are no significant safety concerns for occupants of the space. Specifically, within the TLV, UV-C does not penetrate the eye to cause cataracts or the skin to cause skin cancer. This is supported by authoritative international statements (First et al., 2005; Nardell et al., 2008). Properly sized and installed GUV will provide a continuous 80% reduction in airborne infectious concentrations, under real-life conditions, where infectious sources may be continuously present and shedding virus aerosols. (Nardell et al., 1991; ASHRAE, 2019).

Hg vapor lamps are widely available and relatively inexpensive, although inexpensive lamps may produce ozone whereas higher quality lamps do not. However, Hg lamps are being phased out of the lighting industry in favor of solid-state sources, such as LEDs, and this is true of germicidal UV-C sources as well. There are limited but growing LED UV-C products at present; their power is generally less than Hg vapor lamps. **Although additional research is required, it appears that properly designed and implemented germicidal UV can effectively and safely inactivate airborne microbes that transmit a variety of diseases including SARS-CoV-1 and SARS-CoV-2 (Mackenzie, 2020).**

- ***Room air cleaners using GUV (Hg and LED)*.**

GUV is commonly used in room air cleaners alone with low-efficiency filters or in combination with high-level filtration, although the latter is not necessary in a well-designed system. Portable room air cleaners are often deployed as a quick solution to decontaminating air in rooms where the ability to increase the air exchange rate is limited. One example would be a break room. Room air cleaner efficacy depends on the clean air delivery rate (CADR) relative to room volume resulting in increased Eq. ACH. In practice, if properly sized to the area of application, room air cleaners might increase a typically modest ACH from a central air handling system to Eq. ACH in excess of five/hour, more if desired for airborne infection control. Because air is recirculated, room air cleaners do not increase heating and cooling costs. As such, larger capacity portable air cleaners could be appropriate for use in airport terminal settings. In areas where crowding cannot be avoided and it is not possible to increase the supply air, portable air cleaners with higher efficiency filters (with or without GUV) could be a relatively inexpensive option for increasing effective ventilation, removing some suspended virus aerosols and creating more turbulence to disperse exhaled air in the near fields around an infected person.

Supplemental air cleaners, for a specific application, requires knowing the volume of the space and the ACHs provided by the existing mechanical system. The Harvard CU Boulder Portable Air Cleaner calculator (Allen et al., 2020) was developed to help school building manager's size and select air cleaners for classrooms and could be used by airport facility managers in a similar fashion. Use of portable air cleaners in closed locations such as break rooms or open areas like security screening or at gates is a reasonable application to add more clean air to congested areas or to provide extra protection for employees in frequent contact with passengers.

- ***GUV in ventilation return ducts*.**

GUV can be used in ventilation return ducts to prevent virus from recirculating, converting recirculated air to the equivalent of virus-free outside air for airborne infection control purposes. The amount of GUV needed in ducts is well established; it relates to airflow rates and the susceptibility of the target pathogen. Since there are no human exposure concerns, it is easy to provide enough GUV irradiation to inactivate almost any human pathogen on a single pass. While Hg source 254 nm GUV is being used in response to COVID-19, there are two major limitations of in-duct GUV:

1) For occupants of a room where there is an infectious individual shedding SARS-CoV-2 virus, there is little benefit if shared air will be disinfected only *after* it leaves the room. The most effective air decontamination strategies should focus on interrupting transmission in the room where transmission is likely to be occurring and not once it has left the room.

2) At present, there is no evidence of transmission of SARS-CoV-2 through HVAC systems, although it is theoretically possible. It is likely that the fragility of the virus and subsequent dilution, in room air and then significant further dilution as return air mixes with air from other rooms, results in recirculated air having viral concentrations below the estimated 300-2,000 viral dose needed for transmission (Prentiss et al., 2020).

- ***GUV for surface decontamination.***

Although surface decontamination is not the optimal use of GUV because light travels in straight lines and can miss any shadowed areas or surface nooks and crannies, it is used widely and effectively for many surfaces. Hospitals use high output pulsed Xenon UV source robots to bathe unoccupied rooms with germicidal UV between patients, supplementing hand cleaning and successfully reducing dangerous nosocomial infections transmitted from surfaces. GUV is being used in some airports to decontaminate surfaces, such as bins at security stations and escalator handrails (see Chapter 4). While likely to be effective where the GUV dose is sufficient, the current understanding that the potential for surface transmission of the SARS-CoV-2 virus is lower than originally assumed is expected to limit this application of GUV.

- ***Far UV-C – primarily 222 nm GUV.***

Perhaps the most interesting development of GUV in the last decade has been the production and application of Far UV-C for air and surface decontamination directly in occupied rooms. Far UV has the remarkable properties of retaining similar germicidal effects but being unable to penetrate human tissue sufficiently to cause skin or eye irritation – within the allowable TLV. GUV 222 nm is produced from krypton-chlorine (KrCl) Eximer lamps that resemble Hg sources, but do not have the same safety concerns. Far GUV need not be confined to the upper room application and depends less on room air mixing. It is ideal, for example, to use over food service counters, coffee bars and ticket counters, creating a safe zone of air and surface disinfection between an employee and customers. **In theory, Far GUV can be used widely to safely prevent transmission on a variety of transport vehicles, in waiting areas, and anywhere people gather.** The current limitations of Far UV are cost, efficiency, lamp life, and availability. Although there are no long-term safety studies, most experts are not concerned about long-term effects with the TLV of exposure since only the most superficial cells are exposed and those skin and surface eye cells slough off on a regular basis. Currently, KrCl lamps are expensive to produce and extremely inefficient, compounded by a lamp life of approximately 3000 hrs of continuous use, compared to 10,000 hrs for Hg sources. At present, there are no solid-state sources of Far UV of sufficient power to be useful at room-scale. This is an area of intense research and development, and it is the belief of many that solid state UVC of various wavelengths for various applications will eventually replace both Hg and Kr sources in the not too distant future.

UV lights with wavelengths below 240 nm can produce ozone as a byproduct and require care in design and installation. to ensure that ozone levels produced by their use are limited.

7.4 MODELING TRANSMISSION RISK FOR AIRPORTS

Several mass balance models are available to estimate the risk of transmission of the SARS-CoV-2 virus in indoor spaces. While they differ in terms of their flexibility and ancillary features, the models essentially use the same input data, i.e., physical dimensions of the space and estimates of air exchange rates, either preset or derived from the volume flow of supply air from mechanical air handling systems. The models assume a source (person) is shedding virus at various rates, characterized as either the number of aerosolized virus particles or the quanta (q) of emissions (see Appendix H). A comprehensive discussion of the infectious particles and infectious dose (quanta) methods for estimating the airborne spread of respiratory contagions was presented in the Phase One Report: Assessment of Risks of SARS-CoV-2 Transmission During Air Travel and Non-Pharmaceutical Interventions to Reduce Risk (Harvard APHI, 2020).

The creators of mass balance models cite the same literature in setting the emission rates of viral shedding, with different rates selected based on the assumed activity of the people in a space. For example, the emission rate of an infected person unmasked, talking/laughing and socializing in a restaurant will be substantially higher than if that same person were to be masked and breathing at rest while seated. Given substantial differences within and across person variability in how many viral particles are shed (Anfinrud et al., 2020; Asadi et al., 2020; Buonanno et al., 2020; Morawskaa et al., 2020), simulations will often input high emission rates to explore high-risk conditions. This conservative approach is appropriate in making comparisons across locations or when testing the effectiveness of mitigation strategies within a particular space. Both steady state and dynamic models are available. Steady state models are easier to use and assume the emissions from the source person reach uniform mixing within a space, with some developers offering adjustments to account for imperfect mixing. Dynamic models use shorter time intervals and can provide estimations for the increase and decrease of concentrations in a space. This additional dimension might be useful for determining how quickly a viral load will be eliminated from a room once the infectious person leaves or in estimating the short-term dose resulting from a sneezing event.

A well-mixed environment is generally considered reasonable for many applications, including airport terminals that comprise large volumes of space with occupants spaced randomly. However, the well-mixed assumption will lead to an underestimation of risk when people are in close proximity to one another. So, **the voluminous space of most airport terminals lowers the risk of airborne transmission, while activities such as riding on shuttle buses and trains, queues in lines at security and customs and immigration, and clustering around gates and baggage carousels can create situations where being close to a potentially infectious person represents a higher risk.** Face coverings/masks and physical distancing remain key mitigation measures to be used in these situations.

Both the far-field (FF, i.e., people further apart than 6.6-feet/2 meters) and the near-field (NF, i.e., people are within 6.6-feet/2 meters) from an infected person have been considered in the assessments undertaken by the Science & Technology (S&T) team. **While the risk assessments presented in this chapter are based on actual dimensions in an airport terminal, the models are meant to illustrate generic approaches that an airport might consider as they customize the layered risk mitigation measures based on the architecture, ventilation systems and other aspects of their specific terminals and operations.**

The S&T Team applied computational fluid dynamic (CFD) models to transport vehicles, namely airside buses, shuttle buses and terminal trains. While airport operators are not expected to use CFD modeling, this approach has been employed here to assess the complex flow dynamics in these vehicles. This is similar to how Airbus and Boeing used CFD models to characterize dispersion and removal of contagions in an aircraft, as discussed in the Phase One Gate-to-Gate Report (Harvard APHI, 2020). Only a sophisticated CFD approach is suitable for the circumstances explored here, which focused on understanding the potential exposure, adequate ventilation and dilution air implications of erecting plastic partitions to separate passengers in a security line. The ventilation design for these spaces, following ASHRAE and ACRP guidelines (ACRP, 2010; National Academies of Sciences, Engineering, and Medicine, 2010b) is intended to provide adequate ventilation and dilution air in unobstructed settings. Inserting plastic barriers after the fact could disrupt intended circulation of air and create plastic 'canyons' that would limit dispersion and thereby unintentionally increase concentrations of shed viruses present in the space.

For the airport spaces assessed in this study, the S&T team developed an approach to modeling NF events and then integrated NF considerations into the multi-compartment model. This procedure is described in detail in Appendix I. The modeling exercises undertaken here had the following objectives:

- To provide examples of how risk calculations could be used by airport operators to assist in decision-making related to risk mitigation of SARS-CoV-2 transmission in airport settings.
- To identify any problematic conditions and/or locations where additional risk mitigation strategies may be needed to manage the transmission risk for passengers and employees.
- To explore the relative effectiveness of various mitigation options.
- To provide general guidance to airport operators as they consider occupant densities on conveyances, scheduling the use of gates, regulating the processing times for security checks, decongesting baggage retrieval areas, setting eating (demasking) policies, installing equipment to enhance air exchange rates, using supplemental air cleaners and other strategies.
- The output of the models presented in this section is the probability of infection for susceptible individuals, expressed as percentages. This can be used to estimate the expected number of secondary cases from a given scenario by multiplying the percent number by the number of occupants in that space and then divided by 100.

7.4.1 Exposure estimates using a multi-compartment and single zone model

A variety of approaches to modeling NF and FF exposures to exhaled virus have been used in developing exposure risks. Specific details of the models are given in Appendix I and are summarized briefly, as follows:

- A multi-compartment Markov chain model, which has been used extensively for other exposures, was used to determine that the NF to FF concentration ratio (NF/FF) would range from 2.3-5.6 for the evaluated scenarios. In a later model, a five-times NF to FF concentration ratio estimate was used for several airport scenarios.

- FF estimates using a single-zone model for passenger-occupied zones were used to evaluate the prototypical design for a boarding gate area under different airflows, air exchange rates, and ceiling heights, illustrating the relative importance of each variable compared with the others.

- FF estimates using a single-zone model for employee-occupied zones were used to evaluate employee exposure in the FF for both the security checkpoint and break room locations; the risk from each in masked and unmasked conditions was compared.

- Using both NF and FF exposure risks permitted the calculation of the overall risk from all of the spaces passed through in a typical passenger airport experience. This simulated journey started with a shuttle ride, where the airport operated the transit service between terminals or between the terminal and other locations, and continued through check-in, security, and gate boarding under two conditions; off-site parking was not considered. The first postulated a small less crowded and quick transit airport terminal that could be typical of a small regional airport. The second postulated a larger less crowded more complex transit airport terminal that could be typical of a large international airport. In order to capture both FF and near-field measurement, the S&T Team used the information from the Markov chain model to add a NF exposure risk component to the FF single zone models.

7.4.2 Risk Model Applied To Simulated Security Check Area

Passengers might remain in an airport terminal for an hour or two, at times more, and those with connecting flights perhaps longer still. Airports are also places of employment where staff, concessionaires, service personnel, contractors and federal workers might be on site for full eight-hour or more shifts. As an example, the S&T team modeled a variety of conditions pertaining to security checkpoint staff in an airport terminal:

a) A simulated security area where i) a highly infectious passenger would be present once every hour for a processing time of 10 minutes, with an additional 10 minutes for the concentration of virus particles to decay to background levels, and ii) an employee was present and contagious for the full shift.

b) An employee break room where a contagious employee shares the same shift and time spent in the break room with other staff.

NOTE: All of these models assumed an infectious person was present in the space. Of course, the risk of an infectious person being present is dependent on chance and the prevalence of infection in the travelling population, which can be reduced from that in the community through improved screening activities. In this case, the prevalence in the working and passenger populations could be less than the overall community rate.

The dimensions of the physical spaces were derived from the actual dimensions of an airport passenger screening area and an employee break room (see Table 7.2). The scenarios presented here are intended to represent conditions that could occur and to test the effect of wearing a facial covering/mask on potential exposure risk.

The primary variable being tested was the wearing of a facial covering. Two emission rate scenarios were tested for exposure at the security checkpoint. In scenario 1, the infectious individual (infectious emission) has not been present in the area long enough to reach steady state (i.e., when relevant variables are constant with a source present to reach a constant level that does not change over time). In scenario 2, steady state concentrations were assumed to have been reached. Calculations were then performed under two conditions, one where the infectious individual was not wearing a mask, the second when they were wearing a mask with an estimated exhalation efficiency of 90%. Details of the conditions of the spaces and simulation cases are given in Tables 7.1 and 7.2.

Table 7.1 Key Parameters For Inclusion In A Single Zone Model For A Security Checkpoint And An Employee Break Room

	Security Checkpoint	Break Room
Zone dimensions [m]		
Width	83.2	10
Depth	18.9	5
Height	5.8	4
Supply air rate [m^3/s]	3.9	0.17
Exposure duration [min]	380	60
Number of employees	50	5
Mask wearing		
Percentage of time [%]	(0, 100)	10
Overall mask efficiency [%]	90	90
Breathing rate [m3/h]	0.8	0.8
Quanta emission rate [q/hr]	100	100

The scenario modeled assumed 50 security employees worked an eight-hour shift and, accounting for eating and rest breaks, the time spent in the security checkpoint space was 320 minutes. While on duty, it was assumed that each security employee wore a face mask with a 50% efficiency for inhalation. The resulting risk estimates will shift up or down depending on the actual filter efficiency of the face mask. For the purposes of this example, it was assumed that a highly infectious passenger might be present only half the time as hundreds of passengers are being processed over a day. A highly infectious person might produce as much as 100 quanta (q) per hour under some circumstances and this maximum value was used in the calculations.

Table 7.2 Estimated Individual Risks (%) From Two Spaces Occupied by Security Personnel		
	Security Checkpoint	Break room
Scenario 1 (employee infectious)		
Without mask	(1.4)[1]	4.4
With mask (case and susceptible)	0.14	3.96[2]
Scenario 2 (passenger infectious)		
Without mask	0.084	NA
With mask (case and susceptible)	0.0084	NA

NA not applicable

1 Not realistic since security employees are required to wear personal protective equipment while in public areas
2 Masks assumed to be worn only 10% of the time if main activity in the break room is eating

The results show that the largest potential risk to the employee occurs when spending an hour in the break room, unmasked, with an infectious person present. If no one wears a mask in the break room, then an individual's risk of getting an infection increases by almost 5%. For comparison, the risk of infection from another security employee that is infectious in the same shift during the 60-minute break room exposure is 31.4 times higher than due to the full-shift exposure from an infectious colleague wearing a mask in the security checkpoint area, and 471 times higher than if an infectious passenger, wearing a mask, crosses the security check point every hour.

This is an encouraging outcome as it demonstrates that with appropriate personal protective equipment (PPE) shielding security employees and strong compliance with mask wearing among passengers the risk to staff during passenger contact time would be quite low.

The value of these modeling calculations is to provide a baseline for considering what additional steps could be taken to reduce the risk further. **The results show that the wearing of face masks significantly reduces the exposure risk for both travelers and employees.** The major risk appears when masks are not worn and an individual is in the presence of a potentially infectious individual for a prolonged period. This would suggest that enhanced health screening methods, for example, using pre-arrival molecular or antigen tests and health attestations, could bring value in further reducing the likelihood that infectious individuals would be present to shed viruses while traveling through the airport. To the extent that preventing all infectious people from being present is not possible, then **greater dilution of the infectious source through effective localized air cleaning would help reduce individual risks.**

7.4.3 Risk Model Applied To Simulated Gate Hold Area

For the gate hold area one-hour model, the prototypical design for a boarding gate (departure gate area) was used. The dimensions were 25 meters (82 feet) by 10 meters (32.8 feet), with 150 people waiting and one infected person present continuously emitting 100 q/hour (the upper spectrum of viral shedding) as a high-risk scenario. The time shared in the space between infector and susceptible individuals was varied between 20 and 40 minutes. Three ceiling heights were used to examine this design feature, 4 meters (13 feet), 6 meters (19.7 feet), and 8 meters (26.3 feet). The airflow was set to achieve three, four and six air changes per hour (ACH). The risk assessments and comparisons are based on the Wells-Riley infection model (see Appendix H), and the number of persons infected, based upon the defined occupancy of the modeled space.

Figure 7.4 demonstrates the results from the well-mixed FF model, contrasting the risk of infection for different exposure times (20 versus 40 minutes), ceiling heights and air exchange rates. It is important to note that doubling the duration of time in the presence of an infectious source resulted in an increase more than double the percentage likelihood of transmission. Figure 7.4 also shows that risks can be significantly reduced by increasing the volume of the space as well as increasing the ventilation rates.

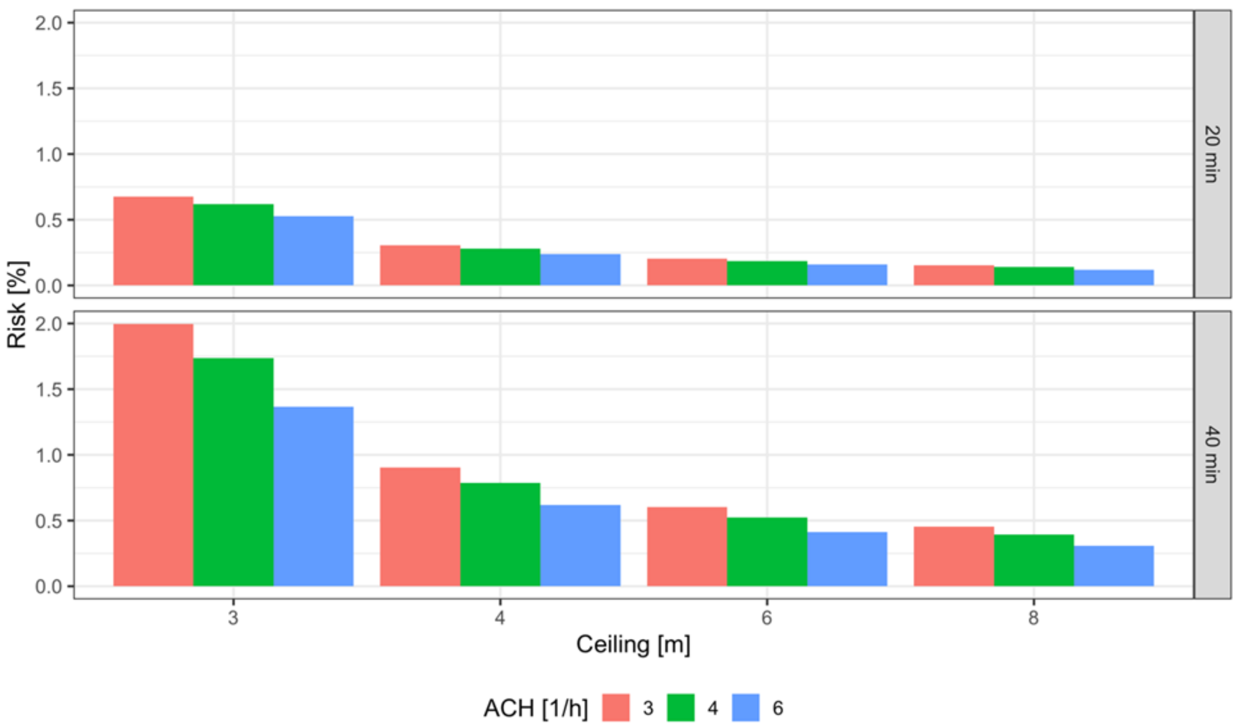

Figure 7.4 Differences in transmission risk by exposure duration, ventilation rate and ceiling height in a boarding gate

7.4.4 Overall, Risk Calculation Across A Typical Passenger Airport Experience

In an effort to characterize the airborne-associated transmission risk from curb-to-plane, the S&T Team estimated the FF and NF exposures in a sequence of transits through the main functional spaces of two different prototypical airports (one large and complex, the other small and less complex) using the modeling methods described in sections 7.4.2 and 7.4.3. This analysis used actual measured space characteristics from a terminal; where these were not available, the team used archetypical ACRP (National Academies of Sciences, Engineering, and Medicine, 2010) design and planning guidelines. While airports have diverse configurations and operational conditions, the results presented here can still serve as a valid reference point to help airport operators identify key aspects that might influence SARS-CoV-2 transmission risks. These include **ventilation rates, space volume and aspect ratios, occupancy density, processing times, activity programming (e.g., virtual queuing, eating at high-density spaces), and the importance of wearing a face mask**.

This section considers the use of an available risk simulation model that airport operators can use to identify the high-risk locations/activities at their airport terminal buildings by inputting into the model the particular characteristics of their spaces, HVAC systems and utilization. As such, it is a dynamic model that can be tailored to a particular airport terminal or other airport setting.

A passenger transiting through an airport terminal engages in a sequence of activities that take place in different functional spaces. During the times they are in each of the locations they may be in close proximity to other passengers (NF) or more distant (FF). In actuality, a passenger has some discretion in the time they spend in crowds. Variances in airport architecture and operation as well as how busy the airport is will influence the likelihood of being in a NF condition.

The following are three different cumulative estimates of risk, assessed for both the prototypical small and large airports with the following conditions:

- Scenario 1, an exclusively FF scenario (best case) where a passenger can avoid crowded locations easily.

- Scenario 2, an exclusively NF scenario (worst case) representing a busy airport with high utilization such as during holiday travel times.

- Scenario 3, a mixed scenario (average case) combining realistic NF and FF risks where a portion of each activity is apportioned to NF and FF situations. Scenario 3 uses an adjustment factor derived from the multi-compartment Markhov chain model (see Appendix I and the observation that aerosol concentrations are likely to be reduced substantially beyond 2 meters (6.6 feet) from an emitter. Having defined the NF area as a 2 m x 2 m square, the proportion of the NF area in relation to the rest of the room area for each functional space was estimated. This defined the probability of being within the NF of a potential infector and allows for scaling risk estimation whenever it is presumed that more than one infector is located in the space (this case was not performed but the model could be easily adapted to this condition).

Simulation inputs for each of the spaces considered are shown in Appendix I. To explore the primary importance of wearing a face mask, the base case for each assessment assumed that no masks were worn and that there was one infectious person occupying the space simultaneously with a susceptible passenger; the infectious person was generating viral quanta at a rate of 100 q/h. Table 7.3 shows the assumptions of time spent in each functional space and assumes both NF and FF exposures for that full duration. The average risks across the different functional spaces vary greatly from 0.10% to a 3.43% likelihood of infection. As expected, the highest NF risk of 7.85% is greater than the highest FF risk of 1.57%.

Table 7.3 Comparative risk evaluation across simulated passenger transits through airport terminals. For identifying differential risk, it was assumed that one infectious person was present in each location/activity and that no masks were worn.

	Prototypical Large International Airport				Prototypical Small Regional Airport			
	Time [min]	Risk Far- field [%] Scenario 1	Risk Near- field [%] Scenario 2	Combination risk [%] Scenario 3	Time [min]	Risk Far- field [%] Scenario 1	Risk Near- field [%] Scenario 2	Combination risk [%] Scenario 3
Shuttle between airport terminals	20	1.57	7.85	3.43	–	–	–	–
Flight check- in	20	0.11	0.56	0.11	20	0.19	0.93	0.19
Security checkpoint	40	0.10	0.50	0.10	20	0.10	0.51	0.11
Terminal train	20	0.80	3.99	1.35	–	–	–	–
Walking to boarding gate/time at concessions	20	0.16	0.78	0.16	20	0.25	1.23	0.27
Boarding gate - Waiting	40	0.62	3.08	0.66	40	0.90	4.52	0.96
Boarding gate - Queuing	20	0.31	1.54	0.48	10	0.23	1.13	0.35
Bus to airplane	10	0.31	1.56	0.48	–	–	–	–

As shown in Table 7.3, the largest contributors to overall risk correspond to shared transportation within the airport (i.e., shuttle, bus, or terminal train). Estimates for airport conveyances were derived from the CFD modeling described in detail in Section 7.5. It is noteworthy that an air exchange rate of 58 ACH was used for all transport simulations, yet the risks of infection are still significant. **As a reference, the modeling suggests that for the same amount of time spent in the check-in area, the FF risk estimate is approximately 15 times higher in a shuttle bus during transport between airport terminals.** Due to the confined space, the probability of being in a NF inside the shuttle is higher, resulting in a larger fraction of the NF risk reflected in the space-specific average risk. This is why the average risk percentage in Table 7.3 is not the arithmetic mean of the FF and NF risk because these numbers are impacted by the size of the space defining the probability of being in the NF. Similar results can be observed for waiting and queuing periods, where people gather in closer proximity and, at considerably higher densities than prior to boarding. Even though the space may be physically larger, the boarding gate waiting and queuing places means virtually everyone will be in NF exposure potential for a significant amount of time and results in a larger fraction of NF risk. This effect is particularly noticeable in terms of the impact it has on increasing the risk profile of the prototypical case of a small regional airport.

Presenting the results separately for each area also revealed additional insights into potential measures to mitigate risk.

Check-in was calculated to be among the lowest relative risk areas, yet, checking-in online or minimizing bag documentation procedures whenever possible are risk-reduction strategies. The risks associated with passing through airport security depend primarily on ventilation and size of the space, both in its capacities for dilution of airborne particles and social distancing, and the processing capacity, which determines the exposure duration. For the prototypical large international airport, a 20-minute terminal train ride was included, which was assumed to be compulsory, so that the only measures to reduce risks are de-densification (see section 7.5 on transportation for more details), or enhancement of the ventilation systems, either increasing flow rates or directing airflow to minimize recirculation.

Both types of airports modelled, i.e., the large and small prototypical airports, included a 20-minute period walking in the airport terminal, for example, to the boarding gate or within concessions. The corresponding risk was computed from the average risk at the check-in, security checkpoint, and holding room. The assessment assumed a very low probability of NF exposure in this activity, resulting in half the risk associated to spending time in the boarding gate area for the same exposure duration.

Simulations of risk while at the boarding gate considered two activities. First, a 40-minute waiting period, where people were assumed to be scattered evenly throughout the entire area of the boarding gate (250 m^2). This was followed by a 20-minute second stage for queuing before boarding, a process described to the S&T Team by airport managers as ‘mushrooming’ of passengers eager to board. The results show a risk increase in the small regional airport boarding gate due to the reduced space available area per passenger, hence a higher likelihood of NF exposures.

Clearly, these risk estimates are calculated for a simulated passenger transit in an airport and do not represent the actual risk. Actual risk to any individual should be much lower. A reasonable way to think about risk of exposure in general is the probability of having an infectious person sharing the same NF airport environment and this would depend on many factors. For example, the current prevalence of COVID-19 positive cases in the U.S. at mid-January 2021 is 75 per 100,000 populations. Some portion of these will be symptomatic and excluded from travel. However, as people infected with SARS-CoV-2 may be pre-symptomatic for several days (He et al., 2020) and 40 to 45% of SARS-CoV-2 infections are considered asymptomatic (Oran & Topol, 2020), such people are potentially spreading virus (Ferretti et al., 2020; Prather et al., 2020, Sommerstein et al., 2020), i.e., they would not be excluded from traveling by symptom screening. Assuming a moderately busy airport, and using the seven-day infection rate for Massachusetts in the U.S., when the study was done, i.e., with 100,000 passengers per day, asymptomatic passengers would be distributed across the day with approximately three infectious persons per 10,000 travelers present at any hour of operations. Passengers, as they traverse a terminal share a common space with only a fraction of those present in the airport at any given time. Even fewer of these fellow passengers would be in the check-in area, using airport transport, in security, or waiting at the boarding gate at the same time. **When considering an airport as a whole, the probability of being in close proximity with a highly infectious person is quite low; hence, any individual has a low risk of contracting COVID-19 at an airport, however, particular attention should be paid by travelers to microenvironments within the airport that may be areas of higher risk.**

However, there are SARS-CoV-2 asymptomatic persons in our population now and not knowing they are infectious, who may choose to travel by air. It is therefore realistic to assume asymptomatic passengers and employees will be present in airports. Therefore, the probability is that NF and FF exposures are occurring, but it is not known where or when these exposures are happening. The probability of having an encounter with an infectious person increases as the number of passengers rises and in congested situations. The analysis in this chapter helps to identify what activities/locations at an airport terminal present a differential higher risk, justifying a closer examination of mitigation strategies that can be layered in a customized fashion to the precise conditions in any one airport terminal setting. An airport can therefore assess its own risk profile and determine a suitable risk mitigation strategy.

The results of these modeling exercises demonstrate the importance for passengers and staff taking thoughtful personal actions in choosing specific microenvironments to spend time in while in an airport terminal, and for airport operators of building or adjusting architecture to house specific functions, determine suitable ventilation conditions and comply with policies for face mask wearing. Some airport operators might be unable to increase the air exchange rates in their air-handling units to mitigate risk sufficiently. In these cases, supplemental air room air cleaners and/or upper room GUV could be used to increase the effective air exchange rate thus providing additional reduction of transmission risk. Further, screening that is more effective and testing of both employees and the travelling public could help reduce the potential for infection by reducing the number of infectious people at the airport.

7.5 SIMULATING TRANSMISSION RISK FOR AIRPORTS DURING TRANSIT AND QUEUING

This study identified two areas of potential concern on the Curb-to-Curb journey for airport passengers, namely (a) while in transportation vehicles conveying passengers between terminals, gate to plane; and (b) when queuing at security checkpoints. CFD was used to investigate the possible high risk of SARS-CoV-2 transmission in these areas. Risk in this context is related to the high density of passengers in a space and the limited number of risk mitigation strategies available. That is, the limited space challenges optimal physical distancing and passengers are required to unmask for security assessment. In these potentially high-risk situations, CFD can offer detailed estimations of airflows, virus and transmission risk using the Wells-Riley equation (Appendix H). These distribution data enabled the S&T team to determine several important findings concerning transmission risk:

1) As shown in Table 7.4, the risk for passengers is well below 1% for passenger activities undertaken while traversing the airport, Curb-to-Curb.

2) The largest contributors to overall risk associated with airports, correspond to shared transportation within the airport boundaries (i.e., shuttle, bus, or terminal train).

3) Queues in security checkpoints, and increased ventilation rates in the breathing zone can help reduce transmission risk for passengers. While plexiglass barriers may aid in maintaining physical separation, they do not help in reducing localized infectious concentrations of viral particles if present. The CFD modeling presented in the following section, shows that tall (8 feet, 2.44 meters) plexiglass barriers serve to concentrate the virus plume in ‘canyons’ that are created by the barriers. Risk may be further increased given that subsequent passengers will inevitably have to pass through potentially higher viral concentrations and remain in the same space perhaps for a prolonged period, while in these checkpoint queuing situations.

7.5.1 Transportation Vehicles Used At Airports

7.5.1.1 Modeling of Airport Transportation Vehicles

This study evaluated three airport transportation vehicles: a passenger transport bus, a shuttle bus, and a terminal train used for intra- and inter-terminal transport. As exemplars, these vehicles provide transfer between terminal and airplanes parked off-gate, and between the terminals in the airport. Figure 7.5 presents the selected vehicles and their corresponding CFD models. In the assessment of virus exposure and potential risk to passengers, important boundary conditions include vehicle geometry, passenger density, and ventilation design/operation. For purposes of this assessment, the following configurations were used based on the specifications of representative commercial vehicles.

- The bus ventilation system has one linear and three round inlets located at each side close to the ceiling. The round inlets are distributed in the front and middle of the bus, which will result in less air supply in the rear part of the bus. Moreover, two outlets are located in the middle of the ceiling.

- In the shuttle ventilation system, there are four inlets on the front panel under the windshield, and one inlet on the air-conditioning unit installed on the ceiling in the rear side. The outlet is only on the air-conditioning unit.

- The terminal train ventilation system has only linear inlets uniformly distributed on both sides of the ceiling. Two outlets are set in the front and rear part of the vehicle, respectively. Using data collected in a previous study evaluating a typical shuttle bus, the vehicles were designed to be ventilated at a ventilation rate of 58 ACH with air supply temperature to be 20.2°C (68.4°F) (Zhu et al., 2010; Zhu et al., 2012). Air was assumed to be 100% clean air to examine the best performance possible for identifying upper limits of passenger loads. To enable higher passenger loads it might be necessary to enhance air cleaning of mechanical systems in transportation vehicles.

For each vehicle, this study created models with specified occupancy rates to investigate the influence of occupant density on local ventilation and the spread of SARS-CoV-2 exhaled by the source person, as summarized in Table 7.4. For illustrative purposes, this study assessed a range of transit times to determine an upper limit to the duration of use. It is recognized intra-airport transportation are expected to be 15 minutes or less. There were six seated passengers in all of the bus models, and eight seated passengers in all of the terminal train bodies. The remaining passengers were standing and uniformly distributed in the cabin. The shuttle models have only seated passengers. It should be noted that the driver was not included in the occupancy for the bus and terminal train because the driver's space is physically separated from the passenger space in the two vehicles. The seated and standing human bodies were simplified and made up of 13 rectangular parts: face, head, trunk (including neck), and left and right arms, hands, thighs, legs, and feet (Zhu et al., 2010; Zhu et al., 2012). All of the CFD models were created with the EquiAngle skewness smaller than 0.78 and aspect ratio smaller than eight, to ensure the grid quality.

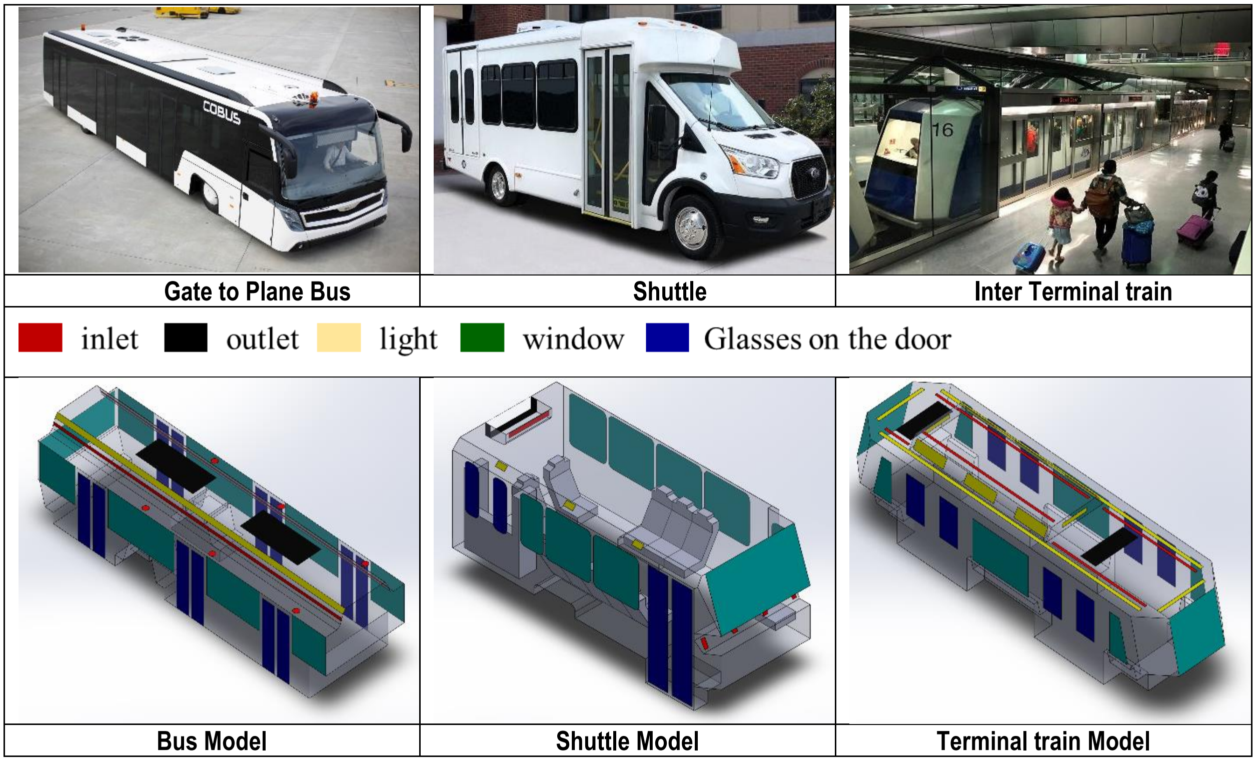

Figure 7.5 Airport transportation vehicles and their CFD models

Table 7.4 Simulation Cases

			Occupancy Conditions			
Vehicle Type	**Empty Volume (m^3)**	**Floor Area (m^2)**	**Capacity**	**Occupancy Rate**	**# of People**	**Occupancy Density (#/m^2)**
Bus	69.7	29.0	110	15%	17	0.59
				25%	27	0.93
				35%	38	1.31
				45%	50	1.72
Shuttle	27.5	13.5	11	25%	3	0.22
				35%	4	0.30
				45%	5	0.37
Terminal train	54.4	23.3	105	25%	26	1.12
				35%	36	1.55
				45%	47	2.02

7.5.1.2 Determination of Source Location

This study used the local ventilation index, i.e., the residual lifetime of air, to determine where to locate the source person. Residual lifetime of air is defined as the mean time for the air at any indoor location to reach the exhaust (Sandberg & Sjöberg, 1983). A longer residual lifetime of air means that the viruses released at that location will stay in the vehicle longer and result in a greater exposure to the viruses. The residual lifetime of air can be calculated with the CFD-based numerical index, i.e., Scale of Ventilation Efficiency 6 (SVE6) by solving the passive scalar transport equation with the reversed flow field (Kato et al., 1992). With this method, a tracer gas is uniformly and continuously generated throughout indoor space, and the air mass from the supply diffuser is gradually contaminated as it is considered proportional to the time elapsed from the time the air leaves the outlet until it reaches the point of removal.

The specifics of the CFD model and method of calculating infection risk are provided in Appendix J.

7.5.1.3 Major Results

Residual Lifetime of Air:

Figure 7.6 shows the distributions of residual lifetime of air in a horizontal cross section at the height of the mouths of seated passengers (4.1 feet/1.24 meters from the floor). The viral source originates in the back of the bus with a seated passenger, represented by the black circle. The other seated passengers are represented by small white rectangles to represent their heads, while the standing passengers have a larger white cross section to represent both torso and arms. Determined by the distance to the outlets, the highest residual lifetime is always observed in the back of the bus. The increase in occupancy results in an increase in the residual lifetime of air, which increases at a steep slope with the distance to air exhaust and significantly decreases when under the air exhaust. Moreover, with an occupancy rate greater than 25%, the stepwise 10% increases of occupancy rate make significant changes in the distribution of the residual lifetime of air, where the mixing gets worse as the bus gets crowded. Similar results were obtained at the height of the mouths of standing passengers. However, the longest residual lifetime of air was always found at the height of the mouth of the passengers seated in the rear part of bus, regardless of occupancy rate. In the shuttle and terminal train, the residual lifetime of air was determined by the distance to the outlet. As a result, the driver was chosen as the source person for the shuttle, and a passenger seated in the middle was chosen as the source person for the terminal train.

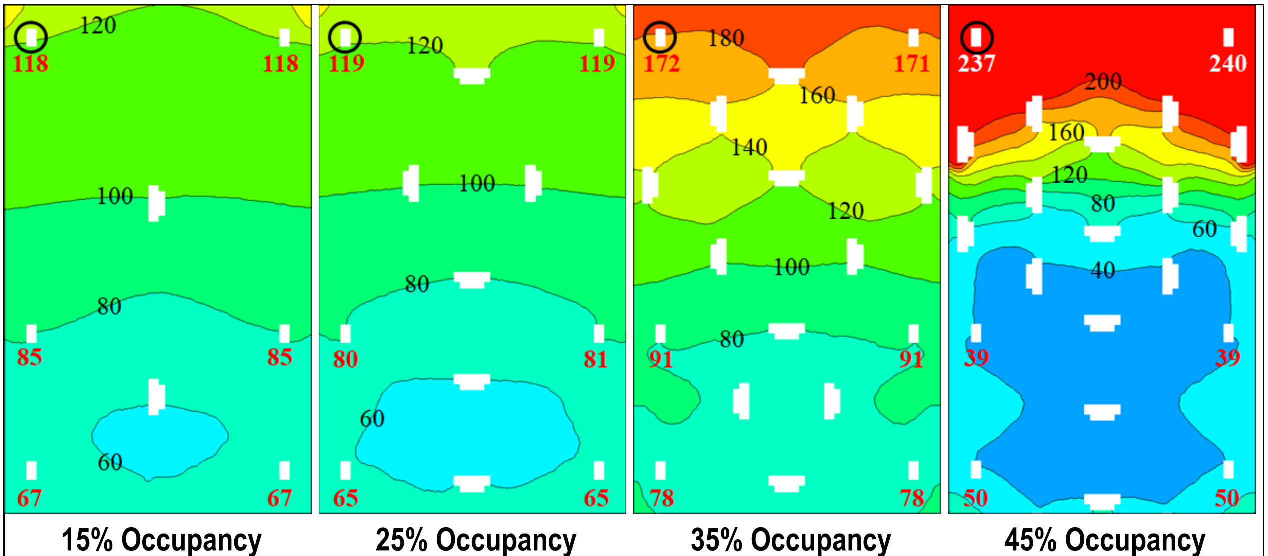

Figure 7.6 The distribution of residual lifetime of air at the height of the seated passengers' mouths while on a bus. The bold red/white numbers are area-weighted averages of the residual lifetime of air at the mouth opening of the seated passengers. *Unit (seconds).* All white shapes represent the horizontal cross-sections of passengers. The larger shapes show torso and arm cross sections of standing passengers, while the small shapes represent head cross sections of seated passengers. The infectious source is designated by the black circle in the rear of the bus.

Influence of Occupancy on Infection Risk:

Figures 7.7 and 7.8 compare the FF and NF infection risks under different occupancy rates, with the infection risk under perfect mixing conditions for up to a 60 minute exposure period. The infection risks were calculated with the quantum generation rate of 100 quanta/hr. The shuttle has the smallest indoor space and has the highest infection risk under perfect mixing conditions. When the vehicle was occupied, the FF infection risk increases, and its increase was highest in the bus and lowest in the terminal train under each occupancy condition. However, the FF infection risk is lower than 5.5% after a 60-minute exposure regardless of occupancy rate and vehicle type. Significantly, NF infection risk was much higher than the FF infection risk at the same occupancy rate in each of the vehicles modelled. In the bus, it reached 34.4% after a 60-minute exposure when the occupancy rate was 45%. As with the FF infection risk, NF infection risk was also highest in the bus and lowest in the terminal train under each occupancy condition. Moreover, in both the bus and terminal train, a 10% increase in occupancy rate from 25% to 35% yielded a greater increase in infection risk than a 10% occupancy increase from 35% to 45%.

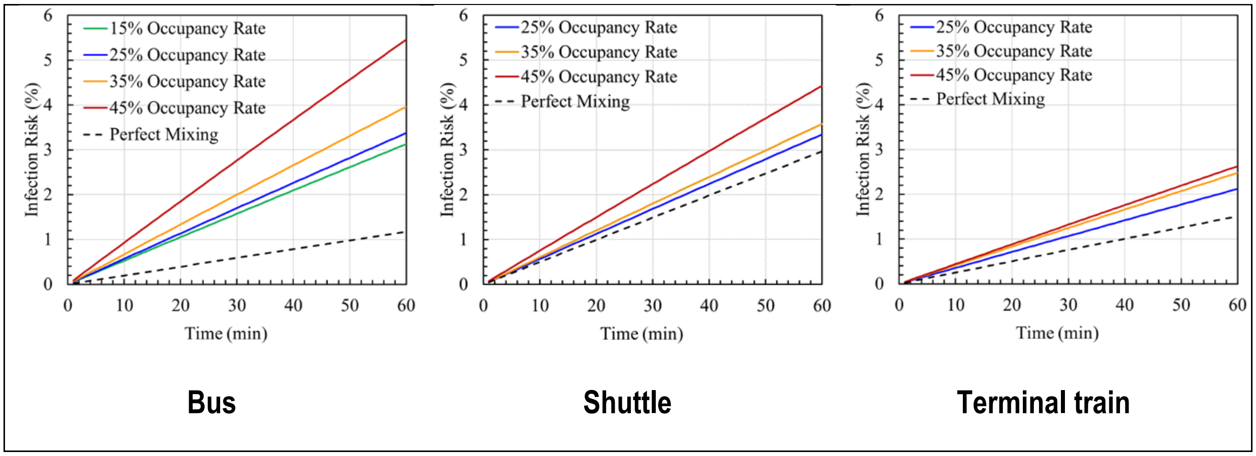

Figure 7.7 Influence of occupancy on far-field infection risk.

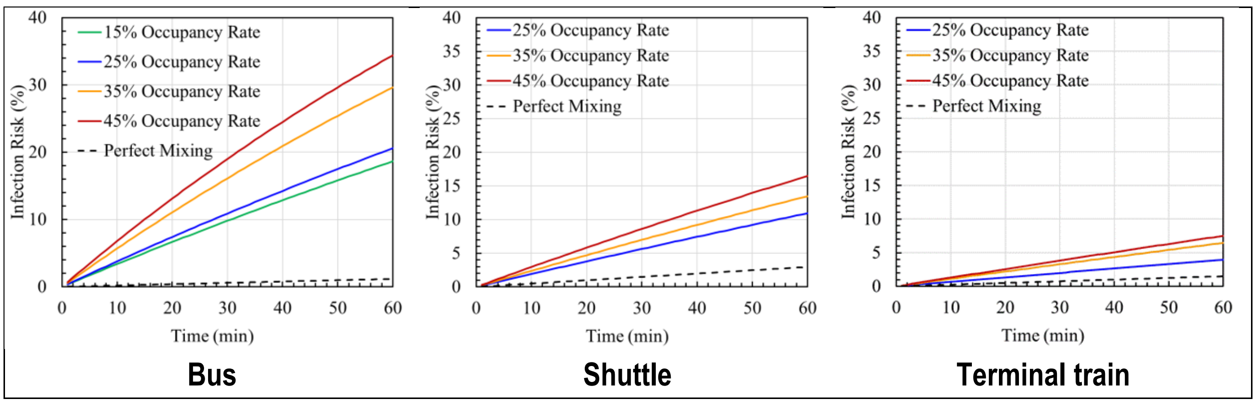

Figure 7.8 Influence of occupancy on near-field infection risk.

Imperfect Mixing Degree (δ):

This study defined an imperfect mixing degree for transportation vehicles, allowing direct comparison of ventilation efficiency in removal of viruses from the passenger breathing zone in different vehicles. This is a multiplier of passenger transmission risk, when compared to the risk for the same vehicle with perfectly running ventilation. It results in perfect mixing and removal of viruses from the passenger breathing zone for a given ventilation rate. This multiplier depends on the vehicle type, its ventilation system design, and occupancy rates. This study defined imperfect mixing degree for both NF and FF in transportation vehicles to explore the relationship between occupancy and transmission risk. This relationship could provide quantitative measures for fleet managers to help decision making with respect to the vehicle occupancy policies.

Table 7.5 Imperfect Mixing Degree Calculated Based on CFD Results		
Vehicle Type	Imperfect mixing degree δ	
	Far-field	Near-field
Bus	2.7	17.5
	2.9	19.5
	3.4	29.7
	4.7	35.7
Shuttle	1.1	3.9
	1.2	4.8
	1.5	6.0
Terminal train	1.4	2.7
	1.7	4.4
	1.8	5.1

Table 7.5 summarizes the imperfect mixing degree calculated based on the CFD results. These results indicate that the impact of imperfect mixing (δ) increases non-linearly with occupancy, and varies with the vehicle type. Its value is always highest for the bus, no matter FF or NF, and regardless of occupancy rate. As shown in Figure 7.9, the occupancy has much more impact on the imperfect mixing degree for the NF than for the FF, especially in the bus. Moreover, comparing the results for the shuttle and terminal train, under each occupancy condition, δ is smaller for the FF but larger for the NF in the shuttle.

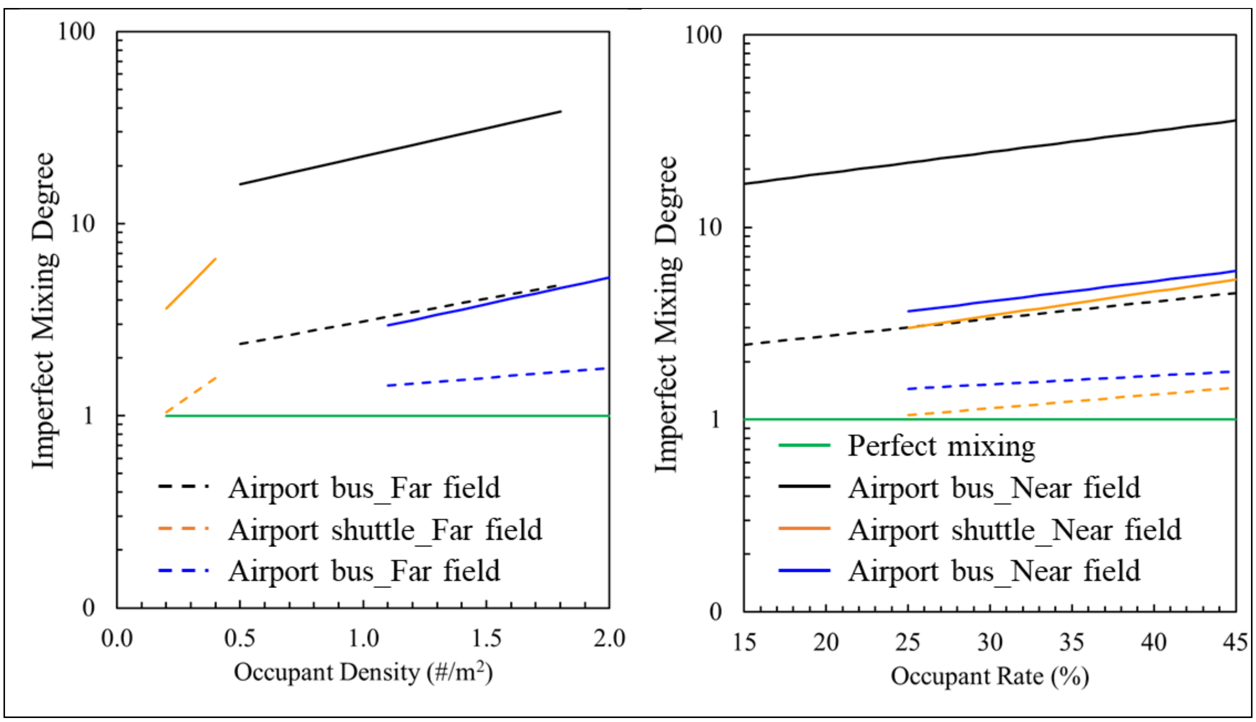

Figure 7.9 Variations of imperfect mixing degree with occupancy (logarithmic scale for vertical axis).

7.5.1.4 Main Conclusions on Transportation Vehicles

Source location, i.e., the distance to the air exhaust, is a decisive factor in the residual lifetime of air and aerosol infection risk in vehicles. Regression models were used to estimate the greatest infection risk caused by the source that has the longest residual lifetime of air and results in potentially highest exposure to aerosolized viruses. As a result, aerosol infection risk is calculated to be less than 5.5% for a full 60-minute exposure in the vehicles for FF transmission, and up to 34.4% for NF transmission in the bus. Under these simulations for the bus and airport shuttle, assuming a ventilation rate of 58 ACH and occupancy rates up to 45%, it is **recommended that, when possible, occupancy time on the bus is limited to 15 minutes and on airport shuttle to 35 minutes to keep an aerosol infection risk within 10% of baseline risk.**

The comparison of infection risk and imperfect mixing degree in the bus and terminal train shows that ventilation design is critical to both FF and NF aerosol infection control. A uniform distribution of air supply and exhaust has the potential to greatly reduce the aerosol infection risk, and mitigate the adverse effect of increased occupancy.

Although the bus had a very light occupant load with the same occupancy density as indicated in Table 7.6, it has an infection risk higher than that in the terminal train. Therefore, strict occupancy control is recommended for the bus.

The S&T team determined several important findings concerning transmission risk:

1) The distribution efficiency of the ventilation system markedly influences the risk in transportation vehicles. Newer vehicles typically have a ventilation system with high air distribution efficiency that promotes good ventilation throughout the entire vehicle volume. However, older vehicles often have zones that offer insufficient air delivery for occupants. This would create potentially high-risk zones in the case where an asymptomatic passenger was present and shedding virus particles in that zone.

2) The risk to an individual passenger would depend on their specific location in the vehicle relative to an infectious person and the distribution efficiency of the vehicle ventilation system. Typically, lower risk would be associated with a passenger experiencing dilution air from an air supply diffuser in a vehicle that removed viruses effectively from the passenger's breathing zone.

3) An increase in passenger density/number in specific transportation vehicles increases risk due to lowering the dilution of airflow per person, as well as reducing the effectiveness of mixing in the passenger's breathing zone. This could result in higher local concentrations of

virus particles and the associated risk of transmission, depending on the proximity to an infectious individual.

4) The imperfect/lower mixing in densely populated transportation vehicles has an important influence on NF dispersion of viruses. This results in an order of magnitude higher risk when compared to risk in well-mixed and well-ventilated vehicle zones. The CFD results show up to 35 times higher NF exposure and up to five-times higher FF exposure in densely populated vehicles.

7.5.2 Queuing At Security Check Points, With And Without Plastic Barriers

7.5.2.1 CFD Modeling Of A Security Area And The Influence Of Barriers Separating Lines Of Passengers

Plastic barriers, as shown in Figure 7.2, are being introduced in some airport terminals to support physical distancing and separate passengers waiting in line at the airport security checkpoint. To explore their performance in reducing transmission of SARS-Co-V-2, the study modeled from an infectious passenger in line and calculated the resultant infection risk.

The CFD models were created based on the dimensions of an actual security check queue area. In CFD modeling, this area was simplified as a cuboid of 82.3 m (270 ft) in length, 18.9 m (62 ft) in width, and 3.66 m (12 ft) in height, with the same floor area (16740 sf^2) as the security check queue area. Due to the spatial symmetry, only half of the space was included in the CFD models as shown in Figure 7.9. Each model had 134 people, comprising eight security officers and 126 passengers. All of the people were arranged at a distance of at least 1.8 m (6 ft) from one another. The passengers waiting in line were supposed to be separated by belt barriers that were ignored in the model in Case 1, and separated by plastic barriers with a height of 2.34 m (7.7 ft) and the bottom edge was 0.1 m (0.3 ft) above the floor in Case 2. The simulation domain includes over 10.6 million meshes in Case 1 and over 14.88 million meshes in Case 2. The quality of the grid system was ensured with EquiAngle skewness smaller than 0.8 and aspect ratio smaller than eight.

The simulation domain's inlet is composed of 13 slot linear diffusers (12 m × 0.025 m), providing clean air of 17^{o}C at an airflow rate of 3.4 m^3/s (2.15 ACH) with an angle of 14.8^{o} downward from the ceiling. The outlet was composed of six square air exhausts of 1 m × 1 m. For the simulation, heat release from people, light and equipment was 130 W/person, 0.7 W/sf (7.53 W/m^2), and 0.33 W/sf (3.55 W/m^2), respectively. As the CFD simulations only account for sensible heat release from the human body, it was assumed that heat release by convection and radiation were 29% (37.7 W) and 38% (49.53 W) of the total heat release, respectively (Murakami et al., 1999). Convective heat release was given at the body surface, while radiant heat release was given to the floor surface. In addition, heat release by lighting was assigned to the ceiling and heat release by equipment to the floor. As a result, heat flux at the human body surface, floor and ceiling surface are 23.84 W/m^2, 12.35 W/m^2 and 7.53 W/m^2, respectively. The detailed boundary conditions are listed in Table 7.6.

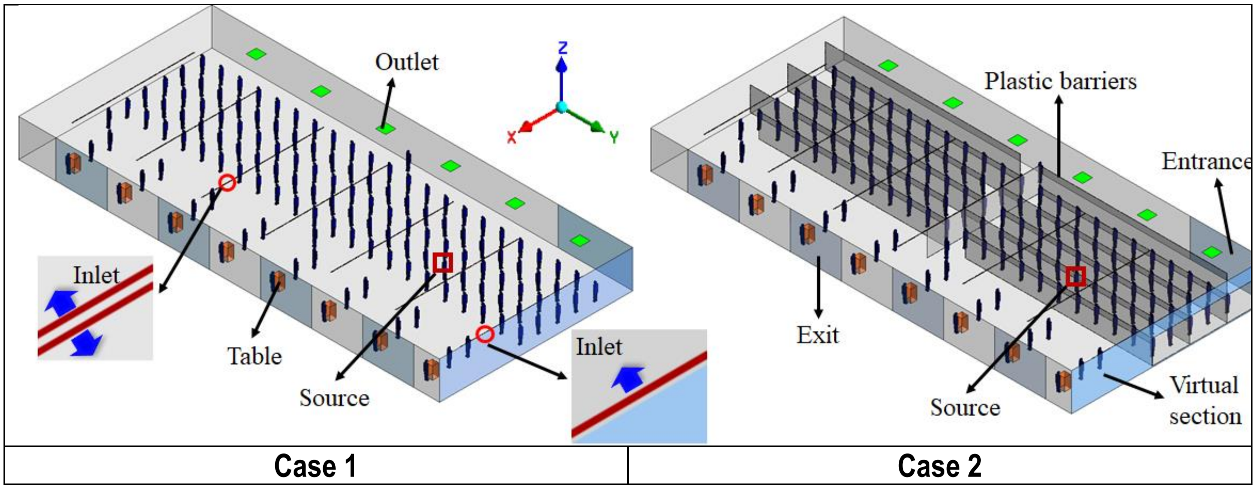

Figure 7.10 CFD models for security check queue area showing open floor plan on the left and a floor plane with plastic barriers.

Table 7.6 Boundary Conditions

Boundary	Conditions
Inlet	V: 3.3 m/s at ±Y direction, 0.9 m/s at -Z direction; T: 17°C
Outlet	Free-slip
Human Body	No-slip, 23.84 W/m^2
Floor	No-slip, 12.35 W/m^2
Ceiling	No-slip, 7.53 W/m^2
Entrance, Exits & Virtual Section	Symmetric
Other Walls	No-slip, adiabatic

As detailed in Appendix J, the Standard k-ε model was applied with the SIMPLE algorithm. The Boussinesq assumption was used for the buoyancy force on convective flows around the surfaces. For the spatial discretization, PRESTO! was used for pressure, with first-order upwind for passive scalar, and second-order upwind for other terms. The convergence criteria were 5×10^{-4} for continuity, velocities, and turbulent terms, 1×10^{-6} for energy, and 1×10^{-14} for passive scaler that represents exhaled bioaerosol attached with SARS-CoV-2. The source person is marked with the red square in Figure 7.10 and the quantum generation rate was set to be 48 quanta/hr (Dai at el., 2020).

7.5.2.2 Major Results on Plastic Barriers

Figure 7.11 illustrates the distribution of SARS-CoV-2 quanta at the height of the passenger mouth at standing level (5.12 feet/1.56 m above the floor). The existence of plastic barriers reduced the spread of infectious particles to the side but increased the infection risk for those standing in the same line, especially the passenger standing behind the one that released viruses.

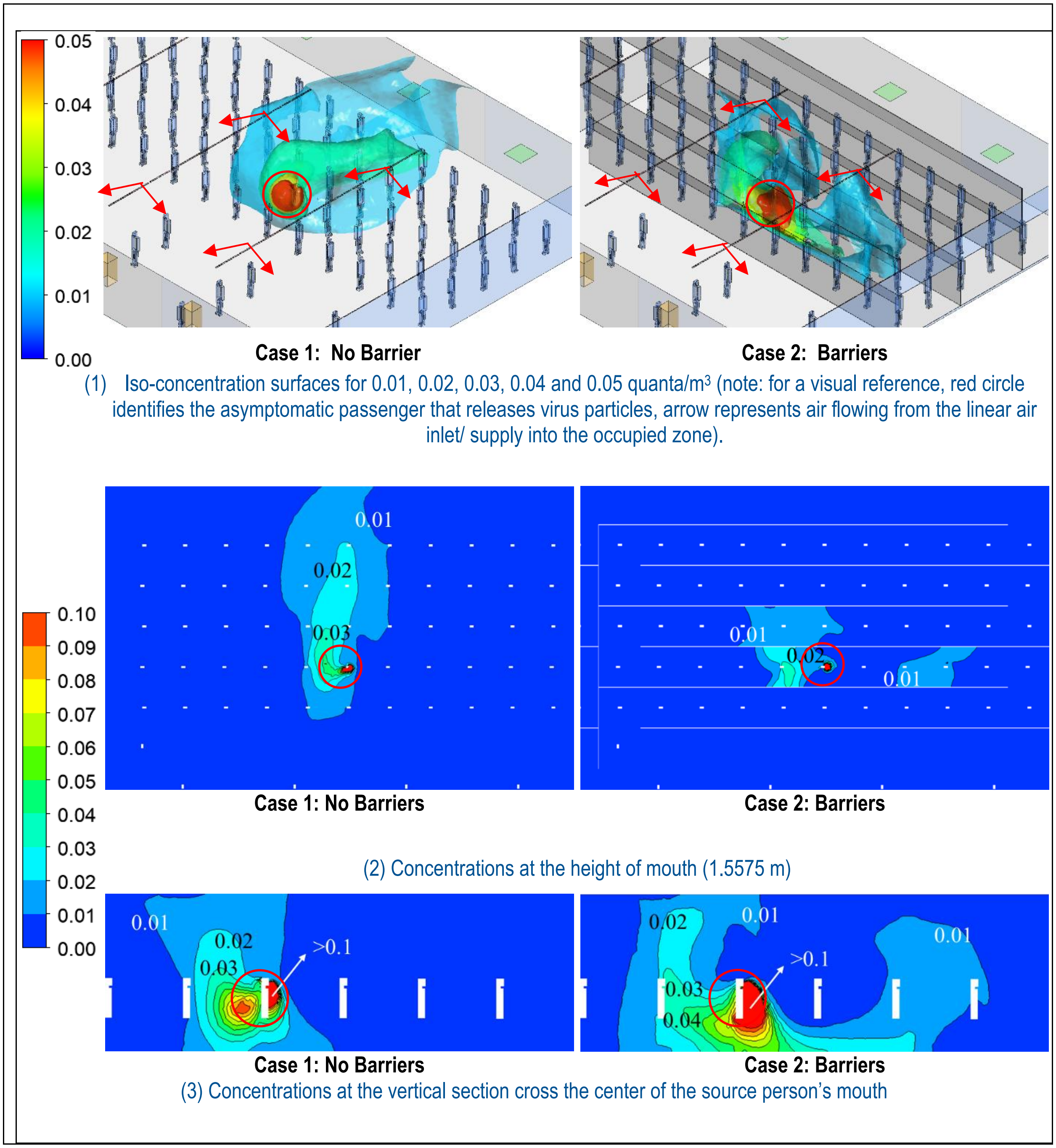

Figure 7.11 Quanta concentration distribution at the height of mouth (1.5575 m). Unit (quanta/m³) – average over 10 minutes following event.

The transmission risk to a passenger queuing in a security checkpoint area was not reduced even in this advantageous setup where the ventilation system with long and effective linear inlet/supply diffusers was pushing a large volume of air directly into the 'canyons' created by the plastic barriers. **Therefore, fast moving queues in security checkpoints and increased ventilation rates reduce transmission risk to passengers, but plastic barriers at best, were not found to help.** Rather, for a less favorable parallel orientation of supply diffusers and queues mixing it is worse because there would be little or no airflow directed into some the plastic 'canyons' that passengers inevitably have to go through. Air with higher concentrations of virus would thus 'linger longer' in under-ventilated plastic canyons.

7.5.2.3 Main Conclusions on Plastic Barriers

Installing plastic barriers can reduce the spread of exhaled virus plumes, but it also can concentrate viruses in the immediate 'canyon'. This locally increased concentration of viruses in canyons could increase the infection risk for the passengers standing in the same queue behind the asymptomatic passenger who released virus particles, as they will have to pass through the same area where virus has been shed and concentrated. **These simulations demonstrate that installation of plastic barriers will require careful evaluation of their potential impact in diminishing the dilution effectiveness and virus removal potential of the existing ventilation system.**

7.6 GENERAL APPROACH TO MANAGING AIRBORNE TRANSMISSION RISK AT AIRPORTS

The ventilation systems of airport terminal buildings are critical for managing the risk of airborne transmission of SARS-CoV-2. Adequate physical distancing and compliance with face mask policies cannot be assured, particularly as travel demand increases. Maintaining high air change rates during higher utilization times will be critical. However, reliance on mechanical systems to deliver sufficiently high air change rates through all occupied spaces of an airport terminal is unreasonable. Congestion among passengers is inevitable, particularly in gate areas, security lines, and baggage retrieval. Further, employees will gather in break rooms and passengers at restaurants and/or bars. If local or state ordinances restrict restaurant services at airports, then passengers and employees may unmask to eat in areas that could be congested. For these reasons, airport operators might consider additional strategies to disperse, dilute and remove contagions in specific spaces.

The modeling undertaken for this chapter examined the adequacy of mechanical ventilation systems in airports and for transit systems associated with airport operations from Curb-to-Curb. The approach taken is generic. It is intended to demonstrate how modeling for SARS-CoV-2 risk assessment can help evaluate the adequacy of airport HVAC systems. Modeling tools can determine whether supplemental strategies are necessary to reduce further the risk of airborne spread of the virus. Not all strategies being proposed by vendors as solutions to airport operators will produce the intended outcome; in fact, they may increase risk as shown here with respect to plastic barrier configurations and the use of some proposed air cleaning technologies. Airports can therefore determine their own NPI strategy using the approach described here but using their own data with the models. Appendix K provides a guide to modeling tools that could be adapted for airport applications.

It is recommended that a qualified HVAC engineering professional audit the airport air handling system and its control settings. Given the WHO (WHO, 2020) and the CDC (CDC, 2020) have confirmed the potential for aerosol transmission of SARS-CoV-2, it is imperative that airport HVAC systems operate at a performance level that will maximize protection from transmission. Reasons for sub-optimal performance include modifications made to the facility over time, deferred maintenance, and overrides of the Building Management Control Systems etc. Experienced HVAC engineers can balance airflows and confirm that the system can supply a specified air change rate to critical spaces where congestion occurs. Air changes per hour and air exchange rates that are appropriate for comfort needs may be insufficient to protect against airborne infections, especially in congested areas.

Airports should consider installing automatic sensors to detect increases in occupancy of passenger area to allow for the rapid adjustment of air supply to those areas and/or take another measure, e.g. queue management. It is common for airport HVAC control systems to adjust flows to meet variable thermal loads. However, this is insufficiently responsive to deal with crowding. With large areas of glass fenestration at airports, they will experience solar heat gains in the day and losses at night that dictate ventilation demands – regardless of passenger volume. Adding CO_2 sensors in the areas of concern may be an appropriate strategy; visual monitoring with object recognition might also provide a timelier response. HVAC professionals and airport facility managers should be able to determine other approaches to provide for maximal airflow to congested areas, for example at departure gates.

In areas where passengers tend to congregate and physical distancing of 6-feet (1.83 meters) is either difficult or not possible to maintain, airport ventilation systems need to be capable of delivering more than six ACH to the travelers' breathing zones during these times. Since there is yet little or no evidence of SARS-CoV-2 transmission through recirculated or mechanical air systems with long ductwork runs and adequate filters, it can be assumed that the supply air is virtually virus free and will not introduce an infectious dose. Therefore, increasing dilution and mechanical removal are reasonable adjustments. Given airports typically have high ceilings and large volume spaces, dilution can be achieved as long as the air is well mixed.

Eating in the gate holding areas or other places where crowding can occur should be strongly discouraged. Otherwise, six-plus ACH may be inadequate to prevent potential exposure to infectious doses. If passengers unmask to eat in crowed areas, then virus-shedding rates could increase, resulting in the potential for near field exposures.

Supplemental air cleaning and enhanced mixing of air should be evaluated for areas where passengers might congregate in close proximity for a period of 15 minutes or more. Properly sized portable air purifiers and upper room UV-C lamps will increase effective air exchange and support dilution and removal of any pathogens including SARS-CoV-2. Increasing air turbulence with mechanical fans in areas where passengers are not physically distanced will help mitigate risk of near-field transmission by increasing dispersion and dilution. Similarly, supplemental air cleaning should be considered for break rooms for staff, especially if those areas are used for staff to eat and interact socially.

As shown in the exemplar vehicles modeled in the analysis described, to maintain transmission risk below 1%, all passengers should be masked and passengers and loads limited to 50% or less for a duration of no longer than 15 minutes. This can serve as an initial guideline until protective levels of ventilation can otherwise be confirmed. These findings are supported by the modeling analysis that assumed the vehicles assessed (airside bus, smaller shuttle bus and terminal train) had their ventilation set at maximum, according to the manufacturer's specification, and that one single infectious passenger was onboard the vehicle shedding at a modestly high quanta/h rate. The actual ventilation rates for the vehicles in use must be evaluated. Many of the existing systems are older than the prototypes used for the analysis in this report. Should their performance be less (or greater) than what was assumed in the analysis and/or their internal configurations are substantially different, then these recommendations will need to be modified accordingly.

Plastic barriers to separate lines where passengers are queueing at check-in, security checkpoints or immigration/customs inspection are <u>not</u> recommended without detailed analysis of the adequacy of air change and mixing of air in the breathing zones of passengers. Partitions might create plastic 'canyons' that inhibit airflow. While these barriers might offer some protection to others waiting in adjacent lines, a passenger in front or behind an infectious person is likely to experience concentrations <u>higher</u> than they would have in an open well-mixed space. The analysis supporting this finding assumed 8-foot partitions in a security area with 12-foot ceilings; this might well be a worst-case scenario. Spaces like departure lobbies with higher ceilings and good vertical air mixing might mitigate concerns for restricted airflow in these plastic sided queues.

It is inadvisable to install disinfection devices in air ducts at this time. While many commercially available devices claim to disinfect supply air effectively, efficacy needs to be demonstrated through independent third party verification before adoption. Furthermore, there are no peer-reviewed published cases studies to support airborne transmission of SARS-CoV-2 through typical central mechanical ventilation systems. Therefore, even if these disinfecting devices actually worked in this space, there would be little gain from installing them in air ducts at airports.

Under no circumstances should disinfecting devices that emit ozone into the air be used in occupied settings. Ozone is a strong oxidizing molecule that can damage respiratory systems, irritate mucus membranes and cause asthmatic symptoms at elevated concentrations. All devices that produce ozone with lamps, or that have the potential to produce ozone by ionization, should be certified to meet UL 867 standard certification (Standard for Electrostatic Air Cleaners; for production of acceptable levels of ozone), or preferably UL 2998 standard certification (Environmental Claim Validation Procedure for Zero Ozone Emissions from Air Cleaners) in order to validate that no ozone is produced.

Modeling tools are available to aid airport operators in assessing ventilation and passenger management strategies to reduce risk of airborne transmission. Some calculations are straightforward and can be readily used by facility managers to evaluate specific spaces, like break rooms. For use in more complex open contiguous spaces at an airport, selecting the most appropriate model and its application may require assistance from professionals who understand building systems and COVID-19 risk model applications and limitations. These tools can provide guidance on operating existing HVAC systems, and determining when supplemental air cleaning may be needed. Further, some models can be used in a dynamic sense to inform airport management on how to optimize ventilation mitigation measures and those that manage passenger behaviors. Models that are more sophisticated can incorporate real time sensor data (e.g., CO_2, occupancy sensors) to optimize risk-reducing ventilation strategies.

Passengers, and to some extent employees working at an airport, have sufficient autonomy to reasonably manage their exposure risk. For example, a passenger is not compelled to crowd around the gate at boarding time and can move away from fellow passengers who are unmasked and eating nearby. Eating at an airport restaurant will be an optional activity for most. Cognizant of activities that diminish distances between passengers, a traveler might reduce the accumulative time in close quarters with others through reasonable adjustments of their own behavior where residual risk remains.

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8.0 CONCLUDING REMARKS

The pandemic has had a profound impact on both public health and the economy, the aviation industry being no exception. Across the globe, some airports closed entirely, others shut one or more terminals (Curley et al. 2020; Dalrymple et al. 2020). Businesses, in general, have spent much of the past ten months adapting to the extraordinary circumstances of the COVID-19 crisis. Airports are focusing their efforts on developing strategies and operations that are informed by science to reduce the risk of disease transmission. The task for Aviation Public Health Initiative (APHI) in this Phase Two Report was to capture the fast-evolving field of SARS-CoV-2 science, translate it for the indoor airport environment, explore risk mitigation across the Curb-to-Curb passenger journey, and consider the impacts of behavioral compliance.

Before the pandemic, the aviation sector in particular, and travel and tourism in general, was experiencing unprecedented growth across all of its business lines. All that changed in a matter of days. The sector reacted quickly, instituting a range of risk mitigation measures that aimed to reduce the likelihood of viral transmission in airport and aircraft settings. From requiring face coverings/masks to be worn at all times, through the installation of hand sanitizing stations and physical distancing signage and communications, airports are making important science-based decisions to manage health and safety. With a focus on the customer experience and the passenger journey, innovation in the sector is strong with an acceleration of digital solutions across the Curb-to-Curb journey.

It is expected that the new hygiene and enhanced cleaning protocols introduced by airports will continue, despite the vaccine program now underway. Similarly, new security and customs protocols are likely to continue to be developed to allow for greater physical distancing of passengers and a reduced touch environment. As shown in the APHI Phase One report (Harvard APHI, 2020), ventilation plays an important part in risk mitigation and this is relevant to the airport environ where more attention to airflow and air handling are recommended as part of the layered NPI approach. The report also highlighted some interventions that should be strongly discouraged, for example, allowing unmasked passengers to eat at congested gate areas or using plexiglass barriers that could create ‘canyons’ in low ventilated spaces.

The airport community had considered a variety of possible pandemic scenarios, and some had developed contingency plans although, few anticipated a pandemic as severe, widespread, and long lasting as COVID-19. As such, there was no playbook for the airport operators to deal with the COVID-19 situation. Rather, as the APHI survey found, airports in general have shown remarkable adaptability and flexibility in rapidly assessing and adopting new practices and protocols. They embraced a wider definition of safety to expand considerations for public health measures, implementing a range of changes that support the sector’s eventual return to a new normalcy. Targeted communication and multi-stakeholder engagement have brought the different airport constituencies together around a shared purpose in tackling the pandemic. Aviation sector bodies and professional networks are serving the industry well as learning is shared and best practices adopted quickly. However, this is a marathon and not a sprint with leaders across the aviation sector embracing new ways of working as they labor to recover the sector. The key objectives are to enhance public health protocols and thus engender the public's confidence in air travel. This will help sustain resiliency of the industry over the long-term. McKinsey and Company forecast travel trends in 2021 and highlighted that leisure travel will bounce back first while business travel lags, with regional and domestic business travel likely to rebound before international (Sneader & Singhal, 2021).

There are challenges ahead from new variants of the SARS-CoV-2 virus that might interfere with the hoped-for reprieve offered by the vaccination programs underway worldwide. Geo-political shifts and the variety of testing regimens, together with lack of health passport global harmonization and standardization efforts, remain potential challenges. New lockdowns and, critically, the rollout of COVID-19 vaccines have and will affect industry recovery. The point is that air travel will only recover as fast as the rate at which people feel confident about becoming mobile again and those attitudes differ markedly by country.

The Phase One and Phase Two reports point to the importance of long-term science-based research programs supported by government and the industry. Given that COVID-19 could be considered a global 'trial run', infectious disease risk mitigation remains a strategic priority for the aviation sector. As such, public health safety measures will be a high priority for the industry going forward as lessons learned from COVID-19 are clear —that is, public health is central to the aviation industry's long-term vitality. Harmonizing approaches across the aviation sector is important, with governments and airport operators following the science and sector-wide standards supporting public confidence and recovery of the industry.

The findings and recommendations in this report show it is possible to implement strategies that mitigate spread of the COVID disease at airports and that the airport operators in the study were taking action accordingly. Following the science and acting upon it can achieve both improved levels of public health safety and industry recovery.

The NPI proposed in this report represent a system of interlinked risk mitigation interventions that when used together can effectively reduce the risk of exposure to SARS-CoV-2 during all phases of the Curb-to-Curb journey. Maintaining public health protective protocols remains an imperative—namely, wearing a face covering/mask appropriately, practicing proper hand hygiene and maintaining physical distancing where possible supported by strategies that encourage behavioral compliance. Enhanced ventilation (in some settings) is an important component of the layered approach.

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APPENDIX A

GLOSSARY OF TERMS

GLOSSARY OF TERMS (IN RELATION TO INFECTIOUS DISEASE)

Aerosol A liquid or solid particle suspended in a gas. The infectious disease community generally considers them to be less the 5 µm in diameter. Aerosols can remain suspended for extended periods of time and contribute to longer range transmission.

Airborne When a virus can be transmitted from person to person by the tiny particles of moisture released from the mouth or nose when speaking, breathing or singing.

Antigen tests Antigen tests are immunoassays that detect the presence of one or more specific antigenic proteins from a virus particle, typically the N protein for SARS-CoV-2, and tend to be highly specific.

Asymptomatic Not showing any signs of illness. A person can be contagious without showing any symptoms.

Ct value The cycle threshold (Ct) value represents the number of RT-PCR amplification cycles needed for a test to rise above the limit of detection of the test. Ct values are inversely proportional to the amount of target DNA in a sample, i.e., how much virus an infected person harbors.

Cluster Two or more people who shared the same space at the same time when they developed symptoms and who subsequently tested positive for COVID-19.

Communicable Similar in meaning as “contagious”. Used to describe diseases that can be spread or transmitted from one person to another.

Community spread Used when the source of someone’s coronavirus infection is unknown.

Confirmed case Someone tested and confirmed to have COVID-19.

Contact Tracing An attempt by public health officials to identify persons who may have been in contact with an infected person.

Contagious Communicable, or able to be passed from one person to another. COVID-19 is thought to be spread primarily through direct contact with an infected individual, by inhaling the microscopic droplets sprayed into the air during a cough or sneeze, or by touching a contaminated surface and then touching one’s eyes, nose or mouth.

Coronavirus A type of microscopic organism that causes illness in humans. “Corona” alludes to the tiny spikes found on the surface of the virus, which scientists thought resembled a crown, when seen through a microscope.

COVID-19 A shorthand way of referring to the novel **CO**rona **VI**rus **D**isease, an upper respiratory infection that was first identified in 2019. The germ that causes it is formally known as SARS-CoV-2.

Droplet Transmission A form of direct transmission, this is a spray containing large, short-range aerosols (tiny particles suspended in air) produced by sneezing, coughing and/or talking. Droplet transmission occurs – in general and for COVID-19 – when a person is in close contact with someone who has respiratory symptoms. People all spray droplets when they talk or breath, a person does not necessarily have to cough or sneeze, these just propel the droplets further.

Epidemic A cluster of outbreaks that have spread from one geographical area to others; also see related terms, “pandemic” and “outbreak”.

Exposure Describes the period of time and/or conditions where a person is in contact with an infected person who may or may not display symptoms.

Fomite An inanimate object that can be the vehicle for transmission of an infectious agent (e.g., bedding, towels, or surgical instruments). There is evidence that the coronavirus spreads via fomites, although, this is a less common route of transmission. (Source: CDC)

Hand hygiene A key strategy for slowing the spread for COVID-19. Washing hands with soap and water for at least 20 seconds is one of the most important steps to take to protect against COVID-19 and many other diseases.

Herd immunity When enough people have developed immunity to a particular infectious disease that the risk of further community transmission is either eliminated or significantly reduced.

Immunity The body’s ability to resist or fight off an infection. The immune system is a network of cells and molecules that help avoid and tackle infections and toxic assault.

Immunocompromised Also called immune-compromised or immuno-deficient describes someone who has an immune system that cannot resist or fight off infections like most people. Can be caused by several illnesses. Some treatments can also cause someone to be immunocompromised.

Incubation period The amount of time it takes for an infected person to start showing symptoms of illness after exposure. In the case of coronavirus, the incubation period is thought to be between two days and two weeks, with the average being five days before symptoms start to appear.

N95 respirator (facemask) Personal protective equipment used to protect the wearer from airborne particles Certified to remove 95% of airborne particles when properly fitted and worn.

Pandemic The worldwide spread of a new contagious disease that has infected a large number of people. WHO declared COVID-19 a pandemic on 11 March 2020. Also, see related terms, “epidemic” and “outbreak”.

Personal Protective Equipment (PPE) Equipment worn to minimize exposure to hazards that could cause illness or injury.

Quarantine The practice of isolating people who appear healthy, but may have been exposed to a contagious disease, such as COVID-19. Quarantines can be self-imposed or government mandated.

R_0/reproductive rate An epidemiologic metric (also called the basic reproduction number) used to describe the contagiousness or transmissibility of infectious agents, usually estimated with complex mathematical models developed using various sets of assumptions. It is an estimate of the average number of new cases of a disease that each case generates, at a given point in time. R_0 estimates for the virus that causes COVID-19 are around 2 to 3, which is slightly higher than that for seasonal influenza (R_0 ~1.2-1.3), but far lower than more contagious diseases such as measles (R_0 ~12 - 18). (Source: The basic reproduction number (R0) of measles: a systematic review, The Lancet, July 27, 2017.)

RT-PCR Real-Time Reverse Transcription Polymerase Chain Reaction (RT–PCR)-based tests use a PCR machine (typically housed in a laboratory) to run a series of reactions to detect the genetic material or nucleic acid of the virus.

Screening A basic series of questions posed by medical personnel to determine if someone should be tested for a particular disease or condition. In the case of SARS-CoV-2, screening may include taking a temperature, and questions about possible exposure to someone with confirmed or suspected COVID-19.

Self-isolation The practice of separating someone who is sick from healthy individuals to prevent the spread of disease. Strategies include confining oneself to a single room/bathroom during the recovery period and not going out in public until the risk of transmission has passed.

Self-quarantine	The practice of isolating oneself from others until it is considered safe. In the case of COVID-19, people who suspect they might have been exposed to the virus are advised to self-quarantine for 14-days.
Sensitivity	Reveals how often a test generates a positive result for people who actually have SARS-CoV-2 (i.e., the true positive rate).
Social distancing	The practice of staying at least six feet (two meters) away from another person, avoiding crowds and gatherings, to reduce the spread of disease.
Specificity	shows the true negative rate of a test, i.e., it represents the proportion of negative tests among people who are actually negative for COVID-19.(the true negative rate).
Super-spreader	A person who, for unknown reasons, can infect an unusually large number of people. Infectious disease specialists say it is common for super-spreaders to play a large role in the transmission of viruses. In what is typically known as the 80/20 rule, 20% of infected patients may drive 80% of transmissions.
Suspected COVID-19	Refers to a patient who is exhibiting COVID-19 symptoms and is currently awaiting test results.
Symptom	Any visible sign of illness that can indicate someone has been infected by a particular pathogen. Typical COVID-19 symptoms are fever, cough and shortness of breath.
TCID50	The concentration at which 50% of the cells are infected when a test tube or well plate upon which cells have been cultured is inoculated with a diluted solution of viral fluid.
Testing	The practice of using blood, urine, saliva, mucus or some other bodily fluid to determine if someone either has a specific condition or has been exposed to a particular infectious disease. In the case of COVID-19, patients typically undergo screening to determine if they need to be tested.
Centers for Disease Control (CDC)	The United States federal health protection organization.
Viral shedding	The period after the virus has replicated in the host and is being emitted.
World Health Organization (WHO)	United Nations organization that monitors and seeks to protect public health around the world.

APPENDIX B

CHARACTERIZATION OF COVID-19 OUTBREAKS BY SETTING IN WASHINGTON STATE AND ESTIMATION OF WORKPLACE-RELATED COVID-19 INFECTIONS IN WASHINGTON STATE, USA UP TO NOVEMBER 10, 2020

CHARACTERIZATION OF COVID-19 OUTBREAKS BY SETTING IN WASHINGTON STATE AND ESTIMATION OF WORKPLACE-RELATED COVID-19 INFECTIONS IN WASHINGTON STATE, USA UP TO NOVEMBER 10, 2020 (CDC, 2020A; WSDH, 2020)

Type of setting	FEBRUARY TO PRESENT				LAST 60 DAYS Sep 22 - Nov 20		
	Number of outbreaks	Percent of all outbreaks	Percent within type of setting	Average number of cases per outbreak	Number of outbreaks	Percent of all outbreaks	Percent within type of setting
All identified outbreaks	**836**			**8**	**289**		
Healthcare settings	**327**	**39%**		**10**	**77**	**27%**	
Long-term care facilities	223		68%	12	44		57%
Hospitals (including psychiatric hospitals)	27		8%	7	8		10%
Outpatient healthcare settings	15		5%	3	10		13%
Behavioral health residential facility	10		3%	5	3		4%
Supported living and home health agencies	52		16%	9	12		16%
Non-healthcare workplace settings	**260**	**31%**		**5**	**110**	**38%**	
Manufacturing worksites	117		45%	5	53		48%
Retail, hospitality, or recreational worksites	60		23%	4	20		18%
Shipping, delivery, & utility worksites	33		13%	4	16		15%
Office-based or other workplaces	33		13%	3	17		15%
Correctional facilities	8		3%	9	3		3%
Other workplaces	9		3%	4	1		1%
Community and social gatherings	**111**	**13%**		**5**	**56**	**19%**	
Food-service establishments	83		75%	3	40		71%
Large social gatherings	13		12%	12	6		11%
Places of worship	15		14%	10	10		18%
Healthcare settings	**327**	**39%**		**10**	**77**	**27%**	
Long-term care facilities	223		68%	12	44		57%
Hospitals (including psychiatric hospitals)	27		8%	7	8		10%
Outpatient healthcare settings	15		5%	3	10		13%
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Food-service establishments	83		75%	3	40		71%
Large social gatherings	13		12%	12	6		11%
Places of worship	15		14%	10	10		18%
Homeless service sites	**71**	**8%**		**6**	**8**	**3%**	
Colleges, childcares, and universities	**63**	**8%**		**13**	**35**	**12%**	
Childcare	45		71%	4	21		60%
UW Sorority/Fraternity	2		3%	265	1		3%
College/Universities	12		19%	6	9		26%
K-12 school	4		6%	3	4		11%
Not yet categorized	**4**	**0%**		**3**	**3**	**1%**	

Major occupational group	Case count	Percentage of total cases in WA	Number employed in WA	(Cases/employed) x 100,000
Healthcare practitioners and technical	1,208	11.1%	171,440	704.6
Transportation and material moving	1,096	10.1%	263,330	416.2
Healthcare support	989	9.1%	144,170	686.0
Production	964	8.9%	78,980	1,220.6
Farming, fishing, and forestry	741	6.8%	22,250	3,330.3
Sales and related	712	6.6%	316,510	225.0
Office and administrative support	695	6.4%	392,860	176.9
Management	667	6.1%	162,850	409.6
Construction and extraction	606	5.6%	169,600	357.3
Personal care and service	579	5.3%	74,900	773.0
Building and grounds cleaning and maintenance	579	5.3%	90,590	639.1
Food preparation and serving related	517	4.8%	299,950	172.4
Education, training, and library	241	2.2%	189,670	127.1
Installation, maintenance, and repair	240	2.2%	133,320	180.0
Protective service	231	2.1%	66,690	346.4
Business and financial operations	203	1.9%	225,940	89.8
Community and social service	178	1.6%	52,280	340.5
Computer and mathematical	111	1.0%	173,940	63.8
Architecture and engineering	97	0.9%	77,020	125.9
Arts, design, entertainment, sports, and media	93	0.9%	49,860	186.5
Life, physical, and social science	54	0.5%	39,850	135.5
Legal	49	0.5%	22,500	217.8

APPENDIX C

SOCIAL SCIENTIFIC INSIGHTS FOR COVID-19 PANDEMIC RESPONSE AND BEHAVIORAL FACTORS RELEVANT TO AIRPORTS AND DISEASE TRANSMISSION

- A shared sense of identity or purpose can be encouraged by addressing the public in collective terms and by urging ‘us’ to act for the common good.
- Identifying sources (for example, religious or community leaders) that are credible to different audiences to share public health messages can be effective.
- Leaders and the media might try to promote cooperative behavior by emphasizing that cooperating is the right thing to do and that other people are already cooperating.
- Norms of prosocial behavior are more effective when coupled with the expectation of social approval and modelled by in-group members who are central in social networks.
- Leaders and members of the media should highlight bipartisan support for COVID-related measures, when they exist, as such endorsements in other contexts have reduced polarization and led to less-biased reasoning.
- There is a need for more targeted public health information within marginalized communities and for partnerships between public health authorities and trusted organizations that are internal to these communities.
- Messages that (i) emphasize benefits to the recipient, (ii) focus on protecting others, (iii) align with the recipient’s moral values, (iv) appeal to social consensus or scientific norms and/or (v) highlight the prospect of social group approval tend to be persuasive.
- Given the importance of slowing infections, it may be helpful to make people aware that they benefit from others’ access to preventative measures.
- Preparing people for misinformation and ensuring they have accurate information and counterarguments against false information before they encounter conspiracy theories, fake news, or other forms of misinformation, can help inoculate them against false information.
- Use of the term ‘social distancing’ might imply that one needs to cut off meaningful interactions. A preferable term is ‘physical distancing’, because it allows for the fact that social connection is possible even when people are physically separated.

Adapted from Van Bavel et al. (2020)

Behavioral Strategies to Enhance Aviation Public Health Safety

The transmission of SARS-CoV-2 intensifies or slows, in part, as a function of human behavior. **Curtailing risky behaviors is key to mitigating the pandemic, its anxieties and its economic implications.** Those behaviors are straightforward: 1) limit contact with infectious droplets and aerosols through mask wearing; 2) reduce contact with potentially infectious individuals through physical distancing; and 3) maintain personal hygiene (hand washing). The recent federal government airport and aircraft face mask requirement will contribute substantially to aviation public health safety.

Recommendations for Airport Operators

Your objective: Achieve compliance with critical public health behavioral norms, to ensure the health safety of the workforce and the public, and to gain the reputation as a facility that takes public health seriously. Build confidence: "We are an airport that cares about your health."

Motivate people to behave and comply: Ensure that communications highlight key risk-reduction messages: 1) Advantages to the traveler; 2) Merits to protecting others; 3) Positive values of compliance; 4) Conformity with science (the "CDC recommends"), social norms and the law; 5) Gain the approval of others; and 6) Regulations that require and enforce compliance.

Ensure consistent and repetitive messaging: Wearing masks and maintaining distance are not natural behaviors. Ensure consistent and repetitive messaging: Reminders are effective when presented across multiple channels and media, as well as through the use of different campaigns that may appeal to differing perspectives.

Personalize the campaign: Airports report person-to-person communications raise compliance. Airport "Ambassadors" can thank passengers for wearing face masks and for physical distancing while monitoring and encouraging compliance from those who do not.

Make it easy to comply and be creative and innovative in finding ways to make public health safety easy and even automatic: Extensive research supports the efficacy of enabling desired behavior by appropriately configuring the environment. Structure the airport experience so that at every turn, compliance with public health behavior is the best, if not the only option.

> **Be ready for resistance:** The pandemic has imposed significant personal difficulty for a variety of people who have experienced it and are reacting to it differently. Be ready to speak compassionately to misinformation. Be empathetic and de-escalate when possible.

Recommendations for Passengers and Airport Employees

Your COVID risk profile: Critically assess your attitudes about COVID-19. Get smart about the science. It is the best way to inform your understanding of risks and ways to remain healthy. Know the health consequences of acquiring the disease for you and others whom you could infect, especially as COVID patients stress hospital capacity.

Plan your trip through the airport: Know your journey from the curb to your gate. Be ready to disinfect hands after touching check-in machines, security bins, or bathroom fixtures. Be mindful of other people, keeping distance as you make your way through potentially crowded security lines, concession areas, restrooms, and gate areas. Although restroom codes generally require negative air pressure to refresh the air, limit time spent in restrooms and avoid crowded facilities. Do not approach crowded areas, such as boarding gates, until it is time to do so. Find less crowded spaces suitable for waiting. Upon arrival, maintain distance when retrieving checked baggage.

Politely ask others near you to comply: If they don't, move away to a safe distance. If that is not possible or gentle and polite persuasion does not work, call upon an airport or airline employee.

Be alert to yourself and to others: Be mindful of your behaviors: it is easy to forget key precautions. Keep both mouth and nose covered. Maintain physical distancing where possible. Be efficient when eating and drinking – do so in uncrowded areas and with minimal face mask removal. Bottom line: Our behaviors are our most important COVID defenses.

Your Health Safety COVID-19 Check List

For Airport Travelers and Employees

YOUR BEHAVIORS ARE YOUR – AND EVERYONE'S - MOST IMPORTANT COVID DEFENSE

Ten reminders before and at the airport:

> Follow testing and quarantine requirements prior to or upon airport arrival. Be part of the solution.
> Monitor COVID-19 symptoms. When sick, isolate. Don't fly. Be responsible.
> If exposed to someone positive for COVID-19, follow CDC recommendations to quarantine and test.
> Plan your trip through the airport - those steps from the curb to your gate - maintaining physical distance.
> Wear your mask at all times and do not remove it except for very short periods to eat or drink.
> Disinfect hands after touching surfaces such as check-in machines, TSA security bins, or bathroom fixtures.
> Minimize time in restrooms and avoid crowded restrooms, even though they have negative air pressure.
> Avoid crowded areas, such as boarding gates, until time to do so. Find less crowded areas to wait.
> Politely request face mask compliance from someone not doing so. If refused, alert an airport employee.
> On arrival, maintain distance when retrieving checked baggage.

Prepared by Faculty of the Harvard T.H Chan School of Public Health, Aviation Public Health Initiative. *Revised February 4, 2021*.

Your Health Safety COVID-19 Check List

For Aircraft Passengers and Crew

YOUR BEHAVIORS ARE YOUR – AND EVERYONE'S - MOST IMPORTANT COVID DEFENSE

Ten reminders on the plane:

> Follow flight crew instructions while on board the aircraft, as is always required.
> Maintain six-foot distance before and after boarding the plane, such as on the jet bridge.
> Keep reasonable distance onboard when stowing and removing overhead luggage.
> Clean hands and your immediate area, including tray tables, armrests and other high touch areas.
> Wear masks at all times during flight, except very short times to eat or drink.
> Politely request face mask compliance from someone not doing so. If they refuse, call a flight attendant.
> Avoid face touching - in particular eyes, nose and mouth - when seated and during bathroom use.
> Avoid congestion in the aisles throughout the trip.
> Alert a flight attendant if someone is symptomatic.
> Do keep hydrated during long flights: Drink prudently by only briefly removing your face mask.

Prepared by Faculty of the Harvard T.H Chan School of Public Health, Aviation Public Health Initiative. *Revised February 4, 2021*

APPENDIX D

QUESTIONNAIRE: REQUEST FOR INFORMATION ON AIRPORT OPERATIONS FOR RISK MITIGATION OF COVID-19

QUESTION GUIDE

FINAL

Request for Information on Airport Operations for Risk Mitigation of COVID-19

Harvard T.H. Chan School of Public Health Aviation Public Health Initiative Science Team

19 October 2020

The Aviation Public Health Initiative (APHI) Technical Science Team at the Harvard T. H. Chan School of Public Health is working on a project to determine the risk of SARS-CoV-2 transmission in airports and on aircraft and to offer science-based risk mitigation strategies to protect the health of travelers and employees. The APHI is sponsored by a consortium of airport and airline operators, and aircraft and equipment manufacturers.

The team now invites Airport Operators and Airport Authorities to contribute their observations and experiences to the study. A series of thematic questions are included, to which your full responses are requested. All responses will be treated as confidential and respondents will not be identified or associated with any particular comments.

To date, the research project has focused on the portion of the air travel experience referred to as '**Gate to Gate**'. For that work, APHI scientists conducted a series of interviews with airlines, aircraft manufacturers and aircraft equipment suppliers. APHI is now broadening efforts to include the airport aspect of the travel experience. APHI is particularly interested in the practices and operations intended to mitigate COVID-19 transmission. This study is called '**Curb to Curb.**' It encompasses airport facilities and processes from departure curbsides to departure gates and from arrival gates to arrival curbsides over the journey.

The APHI team recognize that an important component of restoring confidence in air travel is a shared responsibility that includes airport operators and the airlines. Airports have certain inherent responsibilities to protect passengers and employees. With respect to SARS-CoV-2, airport management responses, as they relate to the protection of public health, include an enhanced cleaning regimen, upgrades to air handling and ventilation, and procedures to protect various stakeholders such as employees, tenants, vendors, visitors and passengers. These efforts play an important role in providing layers of protection and risk mitigation to reduce transmission of the virus and restore traveler confidence.

APHI has developed questions to survey Airport Operators and Airport Authorities. The question guide is arranged across different themes and includes face coverings, cleaning, health screening, new technologies, ventilation, physical distancing and intra-airport transit. As such, APHI expects a range of professionals within Airport Operators and Airport Authorities will likely be involved in completing the survey, with sections collated for return.

This confidential questionnaire is a central part of the research, the results of which will be featured in a comprehensive Project Report. Responses will also be used to guide interviews with some respondents, by arrangement, to take a deeper dive and learn more about operationalizing the layered approach to risk mitigation of COVID-19 transmission.

Engaging in this research will offer respondents an opportunity to share their practices and discuss them with the APHI Harvard Technical Science Team. They will also be able to learn about the activities of peers (anonymously, and without specific attribution). Innovation in the industry will be captured in the Report and shared with sponsors, key stakeholders and with the public.

The Harvard T.H. Chan School of Public Health APHI team thank you in advance for your help with the research and for sharing your time and expertise with us.

PLEASE FEEL FREE TO APPEND DOCUMENTS IN SUPPORT OF YOUR RESPONSES

QUESTION GUIDE

A: Overview of the Responsibilities of Airport Operations for Risk Mitigation of COVID-19

A1. With respect to mitigating COVID-19 transmission, which strategies have you implemented? Please include brief details of any use of personal protective equipment (PPE), barriers between airport employees and passengers (e.g. transparent screens), use of touchless/contactless technology, symptom screening, cleaning and disinfection, decongesting areas and enhanced ventilation etc. How are these responsibilities distributed and coordinated among the many groups (i.e. airlines, TSA, contractors, tenants etc.) authorized to operate at your airport?
Please describe your most challenging issues.

A2. The major routes of SARS-CoV-2 transmission from an infected person to another person are: direct contact with infectious droplets; inhalation of infectious aerosols; and indirect contact with viral particles contaminating inanimate surfaces (fomites). Risk mitigation strategies include physical distancing, wearing a mask that covers the mouth and nose, and disinfection of surfaces – these approaches may be used together (i.e. layered).
What areas or aspects of airport operations concern you most in relation to COVID? Please reflect on the list below:

a. Areas that other leaseholders/concessionaires are responsible for, e.g. restaurants, shops, baggage carousels etc.;
b. Shared management of passenger/employee behaviors;
c. Consistency of 'messaging' and compliance across user groups;
d. Other aspects that you recognize that we have not mentioned.

QUESTION GUIDE

B. Face-Coverings, Masks, and Shields

Face-coverings include respirators, surgical masks, cloth masks, and face shields. This personal protective equipment (PPE) can mitigate transmission of respiratory viruses such as SARS-CoV-2 by:

- capturing respiratory droplets expelled when the person wearing the face-covering breathes, talks, laughs, sings, sneezes, and/or coughs;
- reducing inhalation of respiratory droplets expelled by others;
- restricting a person from touching their face, mouth, and eyes.

B1. Do you require face-coverings? If yes, please detail types and any related usage protocols.

B2. Do your protocols for face-coverings extend to?

a. Employees?
b. Passengers?
c. Vendors?
d. Visitors?
e. Member of the public dropping off/picking up?
f. Contractors?
g. Other?

B3. Do you have any local/state face-covering rules/regulations/mandates to accommodate? If yes, please describe.

B4. How does your airport communicate and publicize face-covering protocols to the groups to which they apply?

B5. Do you provide face-coverings to those that need one free? Via vending machines? Both?

B6. Please describe how compliance with face-covering policies is supported/reinforced. Please distinguish among the different groups, namely passengers, employees, visitor/members of the public/contractors.

QUESTION GUIDE

C. Cleaning and disinfecting to reduce transmission by contact with surfaces

Contaminated surfaces that can transfer disease to a new host are called 'fomites'. Individuals could become infected with SARS-CoV-2 by touching a surface contaminated with the virus and then transferring it to their mouth, nose and/or eyes. Fomites can continue to harbor infectious viral particles until surfaces are disinfected or the virus naturally degrades over time. Fomite transmission refers to transfer of the coronavirus from an infected person to a surface and subsequently from that surface to an uninfected person. Transmission by this route is thought to occur less often than by close contact and very few cases of fomite transmission have been reported. Research suggests that contact with a fomite accounts for less than 10% of the overall risk of transmission of SARS-CoV-2 in certain settings. However, scientists continue to caution that transmission from surfaces is relevant.

C1. What cleaning products, processes and protocols are in use at the airport?

C2. Do you outsource any cleaning to vendors? If so, please describe. How is the quality of this service monitored and contracts amended where requirements have changed given COVID-19?

C3. Do you have, or plan to obtain, any certification from recognized industry cleaning standards, e.g. AAAE Global Bio-risk Advisory Council Star Program or ACI's Airport Health Accreditation Program?

C4. Please describe, or provide a copy of your standard operating procedures, any modifications made for COVID-19 cleaning programs for *high* contact surfaces, under your control. Please include all surfaces, such as restrooms, elevators, escalators, chairs, counters, break rooms, etc.

C5. Do you make any distinction between public-facing surfaces and those restricted to employee surfaces?

C6. Do you make any distinction among those responsible for cleaning surfaces at separate entities operating at the airport such as the carriers, TSA, Customs and Border Protection, various vendors and their suppliers, etc.?

C7. Please describe, or provide a copy of a document, that details any modified cleaning programs for the *non-high* contact surfaces in an airport?

QUESTION GUIDE

D. Health Screening of Airport Employees

D1. Within airport operations, what steps have you or your various stakeholders taken to reduce the risk of a COVID-19- positive **employee** coming into work at the airport and/or its supporting facilities? Please describe the program(s) and their effectiveness, e.g.

a. Attestation of wellness
b. Document verification
c. Temperature checks
d. Virus and/or antibody testing
e. Other

D2. Is there any distinction in the screening protocols used for airport **employees** from employees of vendors, airlines, contract services, security including TSA, Customs and Border Protection and/or others?

D3. Looking ahead, are there any considerations on whether to deploy or trial any other screening technologies or procedures to reduce the probability of a COVID-19 positive **employee** being allowed onto airport property?

D4. Is there on-site health and medical assistance available for **employees**? If yes, please detail the options.

D5. Are there any other concerns with the various airport **employees** and daily operational partners and their employees as they pertain to the risk of COVID transmission?

QUESTION GUIDE

E. Health Screening of Airport Passengers

E1. What steps have been taken within your airport operations to reduce the risk of a COVID-19-positive **passenger** coming into the airport? Please describe the program(s) and their effectiveness.

a. Attestation of wellness
b. Document verification
c. Temperature checks
d. Virus and/or antibody testing
e. Other

E2. Is there any distinction in the screening protocols used for **passengers** traveling through your airport operations compared with those of airport employees? If yes, please describe.

E3. Looking ahead, are you considering whether to deploy or test out any other screening technologies or procedures to reduce the probability of a COVID-19 positive **passenger** being allowed onto airport property? If yes, please describe.

E4. Do you have access to on-site health and medical assistance for **passengers**? If yes, please describe.

E5. As airport operators, what are the main concerns you have about **passengers** coming to your facilities as they pertain to COVID transmission risk?

QUESTION GUIDE

F. Health Screening of Airport Visitors, Public (dropping off/picking up) and Contractors

F1. As an airport operator, what steps have you taken to reduce the risk of a COVID-19- positive **visitor, member of the public (dropping off/picking up) and/or contractors**, coming into the airport? Please describe the program(s) and their effectiveness.

a. Attestation of wellness
b. Document verification
c. Temperature checks
d. Virus and/or antibody testing
e. Other

F2. Is there any distinction in the screening protocols used for **visitors/members of the public/contractors** using your airport operations compared with those of airport employees? If yes, please describe.

F3. Looking ahead, are you considering whether to deploy or test out any other screening technologies or procedures to reduce the probability of a COVID-19 positive **visitor/member of the public/contractor** being allowed onto airport property? If yes, please describe.

F4. Do you have access to on-site health and medical assistance for **visitors**? For members of the **public** dropping off/picking up? For **contractors**? If yes, please describe.

F5. As airport operators, what are the main concerns you have about **visitors, members of the public** and/or contractors coming to your facilities as they pertain to COVID transmission risk?

QUESTION GUIDE

G. New Technologies

G1. What new technologies, if any, have you deployed at your airport to help reduce the transmission of the virus and make the travel experience more contactless? Please describe all that apply, e.g. installation of new biometric technologies; plexiglass/acrylic shields; digital payment systems; surveillance to identify and track passengers, visitors or employees who appear symptomatic, new airport Apps (e.g. that allow people to order food to be delivered to the gate); robots for cleaning or disinfection; antimicrobial coverings on high-touch areas; other.

G2. For any new technologies installed, did any Federal agency share in the costs of installation? For example, TSA and/or CBP helped with plexiglass/acrylic shields.

G3. Do you plan to install any new technologies in the future to help keep passengers and/or employees healthy and safe? If yes, please describe. If no, please describe any actual/perceived impediments.

QUESTION GUIDE

H. Ventilation and Air Handling

H1. Please describe, or provide a copy of a document detailing, the HVAC system in operation at the airport. In particular, give details of filters, maintenance regimen etc.

H2. Please describe the efforts you have made to ensure your HVAC systems are operating as designed.

H3. Have you upgraded any of your air handling systems since COVID-19 struck? For example, improving filter efficiencies. If not, are there any impediments you face in making system upgrades?

H4. If you made changes to any of your air handling systems, did this result in problems? For example, changes in airflow, pressure balances etc.

H5. Are you responsible for the Pre-Conditioned Air system (PCAs) that provides ventilation air for planes at the gates? If not, who is responsible?

H6. The boarding (and deplaning) aspects of air travel are of particular concern given lack of physical separation and uncertainties about airflow and filtration during these transition times. We want to understand the performance specification of the ground air supply systems and PCAs.

a. What are the airflows they provide at different settings?
b. Does the airport have control of these systems?
c. Do these systems have air filters? If so, what are the MERV ratings for these filters?
d. Do they provide air-conditioning and heat for the airplane? If yes, please describe.
e. Do they provide conditioned air for the jet bridge? If yes, please describe.

H7. What are the procedures for operation and maintaining the ground air supply units?

QUESTION GUIDE

I. Physical Distancing

I1. Are you or your various stakeholders enacting any physical distancing measures? If so, please provide details on how you are seeking to maintain physical distancing at the airport and at terminals, e.g. seat blocking, cordoned-off areas, signage, public announcements, technology etc.

I2. **Pre-departure**
-Prior to arrival at the airport, do you send out any communications relating to physical distancing measures passengers will experience once they arrive? If yes, please describe.
-At the airport, do you send out any communications relating to physical distancing requirements passengers are expected to observe? If yes, please describe.
-Have you made any changes to how curbside departure operations are handled? If yes, please describe.

I3. **Departures**
-How do you seek to manage physical distancing at check-in, baggage drop-off, TSA check, on escalators, in elevators?
-Do you use any signage and/or announcements to support physical distancing measures? If so, please provide some examples e.g. photograph/image.

I4. **Airport and Gate Experience**
-Do you require physical distancing measures at gates, restaurants/cafes/food courts, shopping venues and/or restrooms? If yes, please describe.
-Do any of the physical distancing measures in place mean that such services are more restricted? For example, fewer seating places in restaurants. If yes, please describe.

I5. **Arrivals**
-Do you have any procedure(s) in place for arriving passengers, e.g. COVID-19 information stations, health checks, registrations, sanitation stations etc.? If yes, please describe.
-Are any of these procedures mandated by local/state rules/regulations?
-Are you handling baggage claim differently than in pre-COVID times? If yes, please describe.
-Are arrival curbside operations handled differently than in pre-COVID times? If yes, please describe.

I6. As more passengers return to the airport, how do you anticipate handling physical distancing? Do you anticipate any physical modifications to your facilities? What other layers of protection do you foresee as necessary if physical distancing is not possible?

QUESTION GUIDE

J. Intra-Airport Transit

J1. Does the airport include intra-airport transport, such as buses shuttling people to/from airplanes, transit between terminals, train above and/or below ground? If yes, please describe.

J2. Have you changed any of the ways you manage bus/shuttle rides, air tram/train rides, and other means of moving people? If yes, please describe.

J3. Have you changed any of the ways you arrange transfers between terminals and gates given the COVID-19 situation, e.g. dedicated lanes, allowing more time between transfers? If yes, please describe.

J4. Have you implemented physical distancing measures within these intra-airport transit systems? If yes, please specify.

J5. Have you changed any of the ways you manage luggage handling and transfers? If yes, please describe.

J6. Are there any measures to manage pedestrian (i.e. visitors who are not passengers) movements within the airport and terminals? If yes, please describe.

-ENDS-

APPENDIX E

APHI AIRPORT LETTER OF INVITATION TO PARTICIPATE IN STUDY

Aviation Public Health Initiative (APHI)
Invitation to Participate in Airport Research Study by the Harvard T.H. Chan School of Public Health

October XX, 2020

Dear XXXXX (personal contact at airport),

Scientists at the Harvard T.H. Chan School of Public Health are conducting a study to understand the risks of SARS-CoV-2 transmission during air travel, and then recommend science-based risk mitigation strategies to protect the health and safety of travelers and employees. We wish to invite your contribution to this important study.

Harvard scientists leading the study have prepared a confidential questionnaire to survey selected airport operators and airport authorities. Responses from the questionnaire will provide valuable insights into the actions and approaches airports have taken to ensure public health safety in airports during the COVID-19 crisis. Results will also inform whether to request follow-up interviews in order to learn more about particular topics.

We are pleased to invite XXXXX airport to participate in our study. Your participation in this study and the information you provide is protected and confidential. This means that the Harvard APHI team will not identify you or your airport in the report unless explicitly agreed by you.

If you agree to participate, please complete the attached confidential questionnaire. We also have included a request for select photographs and/or copies of protocols/policies you have put into practice. Please return the questionnaire and photographs to xxxx@hsph.harvard.edu ***by no later than November 10, 2020***. As this is an ongoing study, we appreciate your discretion and kindly request that you not speak publicly about your involvement with the project at this time.

If you have any preliminary questions about our study or your participation in our study, please feel free to reach out to scientist Dr. Wendy Purcell, at xxxx@hsph.harvard.edu, or project manager Dr. Leila Roumani, at xxxx@hsph.harvard.edu.

The Harvard T.H. Chan School of Public Health team thanks you in anticipation of your participation in our study. We look forward to incorporating your expertise and experience into the findings of the report.

Sincerely,

Dr. Lenny Marcus	Vice Admiral Peter Neffenger	Dr. Jack Spengler
APHI Co-Director	APHI Co-Director	APHI Lead Scientist
Harvard Chan School	Harvard Chan School	Harvard Chan School

APPENDIX F

SUMMARY DATA FROM QUESTIONNAIRES

A.1 With respect to mitigating COVID-19 transmission, which strategies have you implemented?

Mitigation strategies

PPE	25, require face covering / masks
Physical distancing, signage	17
Physical barriers / plexiglass	21
Playbook for providing safe and secure operating environment	5, creation/distribution of manual
Employee safety precautions	7 1, Updated Communicable Disease response plans; telework where possible, platooning staff to reduce cross contamination 1, Workplace reduced clutter Pre-wrapped eating utensils 2, staggered scheduling, 2 rotating teams to assure business continuity in case an employee tested positive and in close contact with others. Frontline employee schedules spread to keep minimum operational requirements per shift, but also to reduce numbers that can maintain physical distancing. Individual workstations cleaned before and after each shift. Minimized large shift meetings and group gatherings. Shifts are kept separate to allow minimal spread and contract tracing. 1, emphasis on safe practices, 1 on signage and PPE
Health screening room for arriving passengers	1, built a health screening room to facilitate the safe and efficient screening for arriving international passengers
Employee training	4, developed COVID-19 safety training and safe protocols

Highlights:

- At least 12 different mitigation strategies are in regular in use by airports.
- Most airlines mentioned PPE as one of their top mitigation strategies, followed by installing plexiglass barriers.
- Deployment of contactless technologies ranged widely, some in place before the pandemic, e.g., contactless doors. The COVID-19 situation has accelerated the adoption of contactless /biometric processing, boarding, TSA and CBP.
- Physical distancing and signage in support of are common strategies employed by all airports.
- Symptom screening and health attestation for employees is a common strategy.
- Almost all airports have deployed hundreds of hand sanitizer stations.
- Three airports mentioned contact tracing as a strategy they use.

QUESTION GUIDE

	1/2 is online training 2 for cleaning and disinfection providers
Seat blocking or removals	5 blocked or reduced seating in hold rooms, and restaurants to restrict proximities
Contactless technologies / biometric / face recognition	18, have implemented contactless technologies in airport, some already were in use pre-pandemic 4 in restrooms 1 in parking 5, boarding and check-in process 2, bag drop 1, face recognition for employee access 3, contactless TSA security, Global entry 2, simplified arrival at CBP 3, Info kiosks, shops, restaurants 2, elevator 2, hand free doors 1, customer feedback 1, queue management 2, water fountains
Closed-off children areas and business centers	3 2/3, closed-off children play areas
Thermal screening	6, use or piloting thermal screening of employees 1/5 for international arriving passengers 1/5 provides thermometers to employees
Symptom screening/ health attestation	12 ask for employee health attestations before shifts. 1/10 encourages passengers to self-attest
Virtual assistant/self-serve information kiosk/app	2 have a virtual assistant available for customer service
Contact tracing	3 do contact tracing of employees mostly via log in sheets; 1 developing program
Sanitation: Cleaning & disinfection	20 increased cleaning and disinfection practices in airport
Enhanced cleaning/ Electrostatic spraying disinfection	8 have acquired electrostatic sprayers or foggers 2 have robotic floor cleaner fleets 1/5 has a steam cleaning drinking water fountain

QUESTION GUIDE

	1 has a disinfection corridor with safe spray mist
Self-cleaning surface treatment	4 have self-cleaning buttons in elevators, and/or highly touched areas, handrails
Decongesting areas/ reducing capacity in shuttles	6 are decongesting areas using either technology, reduce congestion in managing spaces/gates, crowds, and baggage carrousels
Enhanced ventilation/ filters	9 5 have upgraded filters and increased airflows 1, up to MERV 13 to 15, and even HEPA filter, increased replacement frequency 2 monitoring IAQ, deploying sensors
UV disinfection	10 using UV disinfection 5 using or piloting UV cleaning escalator handrails 3 using in HVAC systems, 2 had it before pandemic 2 UV-C robot or autonomous cleaners
Hand hygiene, hand sanitizer stations	14, hundreds of hand sanitizer stations
COVID-19 testing	2 are partnering for COVID testing
Certifications / accreditation	2, pursued accreditations or certifications

How are these responsibilities distributed and coordinated among the many groups (i.e., airlines, TSA, contractors, tenants etc.) authorized to operate at your airport?

Facilities management	13 airports collaborate with partners for facilities management
COVID-19 task force	1 organized a task force to address challenges and adjustment in airport environment
Barriers installation	4 erected plexiglas walls or shields
Signage	4 mentioned signage as a strategy for social distancing

Responsibilities – distribution and coordination:

- Consistent, regular communication among partners was key to coordinating responsibilities across airport stakeholder groups.
- Facilities management is one of the top areas for collaboration in the airport across multiple parties.
- Some airports collaborated with other parties in installing barriers, signage, and delineating strategies
- Some airports created recovery teams, or ambassadors to increase safe and healthy environment.

Contactless technologies implementation/ autonomous technologies	5
COVID-19 framework/strategy/plan	6
Recovery teams/ health ambassadors/ collaborations	5 created groups to help inform, compliance
Communication	14 mentioned communication for coordination
Videos	1, made videos on COVID-19 precautions
Most Challenging Issues	
Maintaining awareness / awareness of public health orders	5 mentioned maintaining awareness, concerned about COVID -19 fatigue
Scheduling employees to minimize exposure	1
Procuring PPE / hand sanitizer / sanitation items supply	2 procuring PPE, scarcity of supply
Lack of compliance	5 2 deal with lack of compliance through training 1 mentioned that it only takes one person to create the sense that the airport is not safe/ healthy 3 had more compliance challenges early in pandemic
Lack of consistent and clear set of	5 consider it as most challenging

Highlights – most challenging:

- Lack of consistent and clear set of national/industry-wide protocols is one of the most challenging issues for airports.
- Maintaining physical distancing is the other most challenging issue, especially as travel volume increases.
- Lack of compliance, not wearing a mask correctly, and the procurement of PPE, and sustaining business were also challenging issues for many airports.
- Scheduling staggered employees' worktimes, and mitigating transmissions among employees

protocols or standards / conflicting protocols	
Creating a safe and clean environment	2
Mitigating transmissions	1 to limit spread of COVID-19 among employees
Wearing mask correctly	2
Maintaining physical distancing	5 consider that most challenging due to limited space, and increasing volumes
Sustaining business	3 while experiencing significant losses in revenue

A.2 What areas or aspects of airport operations concern you most in relation to COVID?

Areas that other lease-holders/concessionaires are responsible for	9, congregation, following public health orders
Shared management of passenger/ employee behaviors	8 are concerned, 1 is not concerned
Communication, consistency, compliance across user groups	14 concerned, 1 not concerned, some see improvement sin consistency, meet regularly and created plans for pandemic preparedness; 1 uses colorful graphics
Tenant compliance w/Public Health Orders	5
Mask wearing compliance	5
Behavioral aspects	4 1, concerned about activities outside airport that can increase risk for transmission, 1 concerned about mask mandate not welcomed

Highlights – concerns airport operations:

- Lack of consistent and clear set of protocols and policies, compliance across different groups also listed as concern regarding airport operations.
- Maintaining physical distancing is the other most challenging issue, especially when travel volume increases.
- Mask wearing compliance, tenant compliance with public health orders, and in areas where others (tenants) are responsible, also concerns with sharing management of passenger/employee behaviors.
- Also of concern are the choke points at the airport, where is difficult to maintain physical

QUESTION GUIDE

Safe travel environment / critical aviation functions	7 concerned on impacts to airport's critical functions
Pledges	1 took a pledge with airport partners to ensure safety and cleanliness
Physical distancing	8, as traffic volumes will increase, there will less space for physical distancing
Sanitation: Cleaning & disinfection	2 concerned about cleaning and disinfection
Airport "chokepoints"- checkpoints/TSA/ trains/baggage claim, ticket counters, gate areas/queue	4 concerned about areas where congestion typically happens in the airport
Lack of consistent protocols/policies	9, concerned with lack of consistent protocols or policies across agencies, government, employers, also internationally

QUESTION GUIDE

B. Face-Coverings, Masks, and Shields

B.1 Do you require face-coverings?

Face covers / masks required	25 require masks 1 airport mandated 1 only staff required, public recommended
Type of face covering	Covering mouth/nose, without holes, no valves 1 requires surgical or N95 masks and shields in screening areas where officers engage with passengers 1 prefers staff uses reusable cloth mask type
Policies or protocols	17
Exceptions	3 2 conflicts between state mandate (children 10 years old and younger) and city order (children 2 years old and under) Also except for when eating and drinking, and outside when 6' of separation cannot be maintained.

B.2 Do your protocols for face-coverings extend to?

Employees?	23 yes
Passengers?	23 yes
Vendors?	23 yes
Visitors?	23 yes
Member of the public dropping off/picking up?	22 yes 1 no, 2 recommended 4, only if entering facilities, exiting vehicle
Contractors?	18 yes
Exemptions	5, 4 children under 2 or 10, 2 according to CDC guidelines

B.3 Do you have any local/state face-covering rules/ regulations/mandates to accommodate?

If yes, please describe.	16 state orders, 7 County orders 6 City orders 2 departments of health 1 airport order 1 police order

Highlights B.1:

- Almost all airports require everyone to wear face coverings / masks by mandate or order.
- There are only few exceptions noted for children under 2 or 10 years old.
- There are examples of conflicts between the state mandate and the city level on the age for children mask wearing exception.

Highlights B.2:

- Most parties in airports need to wear a mask.
- Most protocols do not measure to ensure compliance.

Highlights B.3:

- There is a large range of mask wearing regulations, from state orders (the majority), to county, city, and airport order. This potentially creates conflicts, highlighted by the airports as a challenging issue.
- Only one example of a fine for non-compliance issued by airport police was given.

Fines	1, $50
Link	3

B.4 How does your airport communicate and publicize face-covering protocols to the groups to which they apply?

Airport employees	
Email:	6
Meetings/employee engagement:	4
Departmental/board/ organization/ commission notifications:	5
Passengers and the traveling public communications	
Email:	none
Website:	8
Social media / influencers media events:	14
Airport app:	2
Other media / Radio commercial / press releases / tours for elected officials / highway billboards:	9 1 highway billboard, 1 on boarding passes
At the Airport	
Visual signage:	24
Verbal Announcements:	20
Airport (health) ambassadors / enforcement staff:	8
Image provided:	2

Highlights B.4:

- Communication with employees is mostly via emails or official notifications.
- Most communications from airports to passengers are passive, via social media, website, and other media.
- Airports do not have access to passengers contact information, only airlines can communicate prior to arriving to the airport,
- At the airport, visual signage is the main way of communication, followed by verbal announcements, and to lesser extent engaging with airport ambassadors or staff.

Highlights B.5:

- Most airports provide free face coverings to passengers or others.
- Most airports also sell masks via vending machines or in airport stores.

QUESTION GUIDE

B.5 Do you provide face-coverings to those that need one free? Via vending machines? Both?

Face covering provision	23
Vending machines / purchase option	16

B.6 Please describe how compliance with face-covering policies is supported/reinforced. Please distinguish among the different groups, namely passengers, employees, visitor/members of the public/contractors.

For passengers / visitors	
Via signage	8
Via verbal announcements	6
Via video	1
Airport (health) ambassadors / customer service staff	5
For employees / contractors	
Via signage	6
Via verbal announcements	5
Training	2
Policy	16
Verification / monitoring	22
Escalation process	9
Bulletins	1

Highlights B.6:

- Support for compliance with face covering policies is mostly driven by signage, verbal announcements, and interactions with airport ambassadors/staff.
- Employee mask wearing is supported by policies, as well as monitoring by mostly airport staff. Passenger monitoring is mostly by airlines.
- There are clear escalation processes if not complying with mask wearing, that are applicable to airport employees.
- There are no escalation processes for passengers not wearing masks, only airlines can deny travel in most airports.

QUESTION GUIDE

C. Cleaning and disinfecting to reduce transmission by contact with surfaces

C1. What cleaning products, processes and protocols are in use at the airport?

EPA N-list approved disinfectants	12
Electrostatic fogging / spraying	11
Cleaning chemicals	12
Airport cleaning and disinfection plan	16
Tenant cleaning and disinfection plans	2
Guidelines or certifications	4
LEED certification	1
Fitwel certification	1
Other airport-made plans	1

C2. Do you outsource any cleaning to vendors?

If so, please describe. How is the quality of this service monitored and contracts amended where requirements have changed given COVID-19?

Outsourced services	20 outsource 2 partially outsource, or optional
Quality control / supervision	15
Airport custodial services	4

C3. Do you have, or plan to obtain, any certification from recognized industry cleaning standards, e.g., AAAE Global Bio-risk Advisory Council Star Program or ACI's Airport Health Accreditation Program?

GBAC-Star Facility accreditation	9 1 interested
ACI's Airport Health Accreditation Program	11 1 interested

Highlights C.1:

- Airports are using EPA N-list disinfectants for cleaning surfaces
- Airports are investing in cleaning technology, such as electrostatic spraying.
- Most airports have cleaning and disinfection plans, and list the chemicals used in their spaces.

Highlights C.2:

- Most airports outsource cleaning services; very few have in house custodial services.

Highlights C.3:

- Many airports have or are planning to apply for ACI Airport Health Accreditation, GBAC-Star or both.

QUESTION GUIDE

Other certification/ commitment	3

C.4 Please describe, or provide a copy of your standard operating procedures, any modifications made for COVID-19 cleaning programs for high contact surfaces, under your control.

Please include all surfaces, such as restrooms, elevators, escalators, chairs, counters, break rooms, etc.

SOPs	23
Supplemental documents	8

C.5 Do you make any distinction between public-facing surfaces and those restricted to employee surfaces?

Public-facing surfaces vs employee restricted surfaces	11 with distinction

C.6 Do you make any distinction among those responsible for cleaning surfaces at separate entities operating at the airport such as the carriers, TSA, Customs and Border Protection, various vendors and their suppliers, etc.?

Airport areas	10 with distinction
Partner areas / quality control	7

C.7 Please describe, or provide a copy of a document, that details any modified cleaning programs for the non-high contact surfaces in an airport?

Additional protocols	17
Link / document	8

Highlights C.4:

- Most airports have cleaning SOPs, and these generally include procedures for safe use of cleaners, PPE while cleaning, and procedures to clean surfaces, and protocols to clean infected areas.

Highlights C.5:

- Almost half of the airports distinguish public facing surfaces from employee restricted ones.

Highlights C.6:

- About half of airports distinguish airport areas that are managed by the airport, but mostly cleaned by contractors.
- Many airports ask partners in charge of cleaning their areas to meet the quality standards set by airport or can assist them to meet standard.

Highlights C.7:

- Most airports have additional protocols for enhanced cleaning.
- Enhanced cleaning consists of chemicals and cleaning technology to disinfect high-touch surfaces, for example these may be electrostatically sprayed or fogged regularly, including daily.

QUESTION GUIDE

D. Health Screening of Airport Employees

D.1 Within airport operations, what steps have you or your various stakeholders taken to reduce the risk of a COVID-19-positive employee coming into work at the airport and/or its supporting facilities?
Please describe the program(s) and their effectiveness

Attestation of wellness/ Symptom screening:	23
Document verification:	1 no
Temperature checks:	14 yes 1 self-administered, 1 if requested
Virus and/or antibody testing:	9
Disciplinary protocols:	2
Staggered work and break times:	2
Working remotely/work from home:	2
Office reduced occupancy / workspace configurations for physical distancing:	1
Screening kiosk:	1
Positive COVID cases reporting / tracking / contact tracing:	7
Paid pandemic leave:	1
Standard Health Protocols:	2
Exhibiting symptoms procedures:	3
Family First Coronavirus Response Act (FFCRA):	1
Wearables for social distancing and contact tracing:	1
Mask wearing compliance:	1

Highlights D.1:
- Employees at most airports undertake health attestations.
- The majority of airports undertake employee temperature checks.
- Some airports begun virus testing and a few are tracking positive COVID cases.
- Other steps taken include staggering work and break schedules. Some offer remote working.
- If an employee exhibits symptoms, airports have procedures.
- A couple of airports have instituted paid pandemic leave.

Highlights D.2:
- About half of airports distinguish screening protocols for employees from those of other airport staff, like vendors, contractors; airlines may have different screening methods.

QUESTION GUIDE

D.2 Is there any distinction in the screening protocols used for airport employees from employees of vendors, airlines, contract services, security including TSA, Customs and Border Protection and/or others?

Vendors/tenants	13
Security/TSA/Customs/Border Protection	9
Visitors	3
Airlines	10
Contractors	11

D.3 Looking ahead, are there any considerations on whether to deploy or trial any other screening technologies or procedures to reduce the probability of a COVID-19 positive employee being allowed onto airport property?

Screening technologies /procedures consideration	10 considering, 8 not considering, 1 maybe
Contactless technologies	2
Thermal screening	5
Facial recognition	1
Covid-19 testing	3
Digital ID	1
Camera systems	1
Screening kiosk	1
Monitoring new technologies	2
new cleaning technologies	2
“on demand” transportation/ autonomous mobility:	1

D.4 Is there on-site health and medical assistance available for employees? If yes, please detail D4. Is there on-site health and medical assistance available for employees?

On-site health and medical assistance for other tenant employees (other than emergency services)	18 no, only emergency services 5 yes, health / medical assistance
on-site medical clinic for board members	1
COVID testing	4
Virtual medical screening	2

Highlights D.3:

- About one quarter of airports are not considering screening technologies.
- Thermal screening is common, followed by technologies for monitoring, testing, contactless, face recognition, digital IDs, camera systems, screening kiosks, cleaning, and autonomous on demand mobility.

Highlights D.4:

- Most airports surveyed do not have on-site health or medical assistance that is not an emergency service.
- Only a few airports had health /medical assistance on-site.
- A couple of airports are offering COVID testing.
- Only one airport provides virtual medical screening.

Highlights D.5:

- Many airports are concerned about COVID transmission to employees from staff of operational partners.
- Many are concerned about tenant’s staff.

D.5 Are there any other concerns with the various airport employees and daily operational partners and their employees as they pertain to the risk of COVID transmission?

Any concerns on employee/ partners COVID transmission	11 yes 7 no concerns; 2 not aware
Employee health & safety education	1
Transmission risk to volunteer customer service/elderly volunteer workforce	1
Implementing a COVID testing regime	1
Employee/tenant employee compliance	5
Guidance by different authorities is not consistent	1
Airport employees working in close proximity	1

QUESTION GUIDE

E. Health Screening of Airport Passengers

E.1 What steps have been taken within your airport operations to reduce the risk of a COVID-19-positive passenger coming into the airport? Please describe the program(s) and their effectiveness.

Attestation of wellness / symptom screening / health interview screening	9 passenger attestation by airlines during check in 1 self-screening via signage 1 interview by health screener 1 by arrival form 5 no, as not done by airports
Document verification	7 no 1 yes, by airlines 4, yes, 2 to arriving passengers, 1 to departing passengers
Temperature checks	4 yes 1 yes, but by airline
Virus and/or antibody testing	5 yes
Face coverings	6
Reduce touchpoints / interaction / physical distance	2
Communication	6
Reducing access to only ticketed passengers and employees	5
Procedures/protocol if COVID-19 positive passenger arrives	3
AA Rapid Testing	1
Tracking COVID-19 positive cases	2
Hand sanitizer stations	2

Highlights E.1:

- Airports do not typically undertake health attestation of passengers.
- Most attestation to passengers is done by airlines during check-in.
- One airport encourages self-attestation screening.
- One airport uses health screeners to interview passengers.
- Only two airports verified arriving passengers.
- Most airports rely on communication to reduce risks with passengers, encouraging proper use of face coverings in the airport, reducing touchpoints, and denying access to non-traveling visitors.
- Few airports have procedures in place to deal with COVID positive passengers arriving in airport.
- A few airports offer rapid testing.

QUESTION GUIDE

E.2 Is there any distinction in the screening protocols used for passengers traveling through your airport operations compared with those of airport employees?

If yes, please describe	15

E.3 Looking ahead, are you considering whether to deploy or test out any other screening technologies or procedures to reduce the probability of a COVID-19 positive passenger being allowed onto airport property?

If yes, please describe	14
safe travel corridors, or Air bridges	1
On-site testing facilities consideration	5
New technologies	5

E.4 Do you have access to on-site health and medical assistance for passengers?

on-site health/medical clinic	7
rapid testing provision	4

E.5 As airport operators, what are the main concerns you have about passengers coming to your facilities as they pertain to COVID transmission risk?

Large number of connecting passengers / increased activity.	2
Passengers unfamiliar with public health orders	1
ability to create an environment where our passengers feel safe / safe operation	2
Maintaining social distancing throughout the entire passenger journey / when traffic volumes pick up	4

Highlights E.2:

- Almost all airports distinguish screening procedures between passengers and airport employees, rarely screening passengers.

Highlights E.3:

- More than half of the airports are considering acquiring or testing new screening technologies or procedures.
- Most are looking into new technologies, then considering on-site testing facilities.

Highlights E.4:

- Less than half of airports have on-site health or clinic available to passengers. Fewer are providing rapid testing.

Highlights E.5:

- About half of airports are concerned about transmissions in airport, or airport becoming a hotspot spreading the virus, and fear for having adverse impacts to airport operations.
- Less than half are also worried about asymptomatic transmission, and some are concerned about maintaining social distancing when travel volumes increase.

QUESTION GUIDE

Attestation of health	2
Mask usage	2
No compliance with CDC Guidelines	3
Knowingly Ill passengers, traveling while sick	7
Transmissions / Airport being a hotspot for the spread of virus / adverse impact to airport operations	10
Asymptomatic transmission	7

QUESTION GUIDE

F. Health Screening of Airport Visitors, Public (dropping off/picking up) and Contractors

F.1 As an airport operator, what steps have you taken to reduce the risk of a COVID-19- positive visitor, member of the public (dropping off/picking up) and/or contractors, coming into the airport?

Please describe the program(s) and their effectiveness.

Attestation of wellness, health screening	7
Document verification / sign in sheet	1
Temperature checks	4
Virus and/or antibody testing	5 no
Face covers / masks	8
Physical distancing	6
Symptomatic member of the public	1
Hand hygiene	2
CDC guidelines / policies	2
Discouraging visitors (non-travelers) meeters and greeters / meetings / no pick up / drop off programs	8
Parking management	1
Virtual meeting	1

F.2 Is there any distinction in the screening protocols used for visitors/members of the public/contractors using your airport operations compared with those of airport employees?

If yes, please describe	11

F.3 Looking ahead, are you considering whether to deploy or test out any other screening technologies or procedures to reduce the probability of a COVID-19 positive visitor/member of the public/contractor being allowed onto airport property?

Screening technologies	6
Contactless temperature technology	2

Highlights F.1:

- About half of airports incorporate health screening of visitors and contractors, and mandate wearing of a face covering/ mask, and rely on physical distancing.
- A couple of airports discourage non-traveling visitors coming inside the airport.

Highlights F.2:

- Almost half of airports distinguish screening procedures between airport visitors and employees.

Highlights F.3:

- One quarter of airports are considering acquiring or testing new screening technologies or procedures.
- Most are looking into new screening technologies, contactless temperature screening technology, and emergent technology.

Highlights F.4:

- Less than half of airports have some limited medical assistance for airport visitors or contractors, mostly emergency service by paramedics.

Highlights F.5:

- More than half of airports are concerned about having airport visitors or contractors that are COVID positive, symptomatic or asymptomatic.

Visitors to follow state guidance	1
Emergent technology consideration	1

F.4 Do you have access to on-site health and medical assistance for visitors? For members of the public dropping off/picking up? For contractors?

Visitors / Members of public	9, some limited or emergency
Contractors	8

F.5 As airport operators, what are the main concerns you have about visitors, members of the public and/or contractors coming to your facilities as they pertain to COVID transmission risk?

Visitors / Members of public	15 13 Visiting as a Positive COVID cases (asymptomatic / symptomatic)
Mask compliance	2
Contractors	9

G. New Technologies

G.1 What new technologies, if any, have you deployed at your airport to help reduce the transmission of the virus and make the travel experience more contactless?

New technology evaluations	6
biometric technologies for boarding / processing / exit processing	6
Biometric screening for employees / contactless security card readers / clocks	2
Biometric technologies for bag checking	2 piloting
Biometric facial technology in US customs (Simplified Arrival)	5
Digital ID & forms / Mobile passport control	1
Contactless electronic boarding pass / check in	4 mention that airlines have implemented it
Contactless path & entry reservation app for physical distancing and reduced congestion / contactless reservation for ground transportation	4 airports, 1 of 2 in process of implementation 1 of 2 has it through an app– already using it.
Contactless restroom fixtures and stall occupancy technology / restroom feedback	6
plexiglass/ acrylic shields	23
Thermal screening cameras	5
Self-service / Information kiosks flight scanners	4
Information apps / digital assistant	4
Contactless garbage bins	1, prior to pandemic
Digital payment systems	6

Highlights G.1:

- Almost all airports had installed plexiglass barriers, use airport apps and contactless technologies.
- Different types of biometric technologies are being explored by airports, such as simplified arrivals with CBP, employee screening and clock in.
- Contactless ordering via airport apps and contactless food pick up.
- Others contactless technologies are managed by airlines, such as boarding and check-in.
- Restrooms, especially those located airside, may have contactless fixtures.
- A couple of airports are piloting digital assistants or information apps.

QUESTION GUIDE

Surveillance to identify and track passengers, visitors or employees who appear symptomatic:	1 via CCTV
New airport apps/contactless technologies/online ordering/ contactless pickup (e.g., that allow people to order food to be delivered to the gate):	12
UV disinfection:	9
Robots for cleaning or disinfection/self-sanitizing:	9
Electrostatic Sprayers:	5
Hands-free door openers:	3
Contactless luggage check/ self-tagging:	1
Health/ symptom screening/ attestation:	1
Antimicrobial coverings on high touch areas/antibacterial TSA bins/elf sanitizing coverings:	10
Hand sanitizer stations/ interactive map / contactless:	5
MERV filters/ventilation enhancements/disinfection/ IAQ monitoring:	4
Infectious disease risk software/global surveillance:	1
Signage:	1

G.2 For any new technologies installed, did any Federal agency share in the costs of installation?

Help from TSA and/or CBP, Federal government	10 yes, mostly for plexiglass
CARES Act	3
FEMA	1
contactless kiosks	1, pilot by private partner
Line queue guards	1, no federal help

Highlights G.2:

- Most federal agency funds went to installation of plexiglass barriers at airport.
- A few airports used help from CARES Act for the barriers, and FEMA.

QUESTION GUIDE

G.3 Do you plan to install any new technologies in the future to help keep passengers and/or employees healthy and safe?

New technologies, in general:	11
Thermal cameras / screening:	3
New cleaning technologies:	2
UV disinfection:	7
Autonomous UV disinfection robot:	1
Contactless technologies:	10
Queuing/physical distancing technology/reduced congestion:	7
Antimicrobial coverings on high touch areas:	3
COVID testing:	4
Air ionizers:	2
HVAC technologies:	3
Self-service bag drop:	1
Contactless, ‘safe-distance’ employee screening/security:	2
Any actual/perceived impediments:	funding the greatest challenge

Highlights G.3:

- About half of the airports are planning to install new technologies in the future; most of them are looking at contactless technologies, and remote queueing and reservation technology to reduce congestion.
- Autonomous cleaning technology as well as UV disinfection robots are technologies being considered by airports.

H. Ventilation and Air Handling

H.1 Please describe, or provide a copy of a document detailing, the HVAC system in operation at the airport.

Digital control systems	5
CO2 sensing	2
Air handling units (AHU)	12
Cooling / heating	8
Rooftop Package Units (RTU)	1
HVAC Filters / MERV	22
UV systems	8
Ionization	1
Increased ventilation rates	3
Positive pressure within facilities.	2
In-house maintenance regimen	16
Outside vendors maintenance	3

Highlights H.1:

- Almost all airports have MERV filters in the HVAC systems before the pandemic or upgraded due to COVID.
- Most HVACS utilize air-handling units with UV light systems and ionization installed or are considering upgrading the system.
- Most systems have an in-house maintenance regimen.

H.2 Please describe the efforts you have made to ensure your HVAC systems are operating as designed.

Systems O&M	23

Highlights H.2:

- Most systems operations performance via O&M procedures, mostly handled in house.

H.3 Have you upgraded any of your air handling systems since COVID-19 struck?

HVAC systems / Air filters upgrade	10 upgraded 2 considering
UV-C light technology	3 upgrades 1 had prior to pandemic
Bipolar ionizer / photo catalytic oxidation (PCO)	3 1 testing
Increased duct cleaning	1
Deficient or uncovered areas / gaps	1

Highlights H.3:

- Five airports have upgraded the HVAC air filters to MERV ratings due to the pandemic, and two more airports are considering upgrading the filtration systems.
- In addition, UV-C light has been used in couple of upgrades or had been installed years prior to the pandemic.

H.4 If you made changes to any of your air handling systems, did this result in problems? For example, changes in airflow, pressure balances etc.

QUESTION GUIDE

Any changes?	7 yes 1 evaluating
Change in settings for 100% fresh outside air / ASHRAE Covid recommendations	2
CO2 monitoring	1
Automatic airflow adjustment	1
Demand-controlled ventilation	2

H.5 Are you responsible for the Pre-Conditioned Air system (PCAs) that provides ventilation air for planes at the gates? If not, who is responsible?

Areas where airport is responsible	17
Areas where airport is NOT responsible	5

Highlights H.4:

- Many of the changes made to the AHUs have been driven by programming, ventilation, and filtration efficiencies for more demand-controlled ventilation, and for some airports to meet ASHRAE airflow recommendations aimed at reducing COVID risk. Some of the efficiencies have generated energy savings in couple of airports.
- Other strategies are specific to the system age and are being evaluated at couple of airports.

Highlights H.5:

- In most cases where there are PCAs, the airports are responsible for the system management. In the case where the airports are not responsible, usually the airlines manage the PCAs.

QUESTION GUIDE

H.6 The boarding (and deplaning) aspects of air travel are of particular concern given lack of physical separation and uncertainties about airflow and filtration during these transition times.

Ground air supply (GAS) systems and PCAs airflows / different settings	12 varies by aircraft, PCA unit, setting
Airport-controlled systems	7
GAS/PCA systems have air filters, which MERV rating	12
GAS/PCA provide air-conditioning and heat for the airplane	16
PCA provide conditioned air for the jet bridge or Passenger Boarding Bridge (PBB)	9

H.7 What are the procedures for operation and maintaining the ground air supply units?

original equipment manufacturer (OEM) recommendations	7
O&M via Computerized Maintenance Management System	1
O&M procedures	11

Highlights H.6:

- The settings and airflows in most of the GASs and PCAs vary according to the aircraft serving, the PCA manufacturer.
- About half of the airports have GAS/PCA systems that use filters with MERV ratings, or washable filters, or provide 100% fresh outside air.
- Most GAS/PCA units can provide AC and heating to aircraft.
- In less than half of airports, the PCA can provide AC for jet bridges.

Highlights H.7:

- Almost all airports have O&M procedures, and many follow the OEM recommendations. One airport GAS does the O&M via CMMS.

QUESTION GUIDE

I. Physical Distancing

I.1 Are you or your various stakeholders enacting any physical distancing measures?

seat blocking / removal	11
Changes to boarding/ deplaning process	2
cordoned-off / closed areas / capacity control / queues	10
signage	23
public announcements	18
technology	2
Areas where social distancing is difficult	7
Airport (health) ambassadors	2

I.2 Pre-departure

Prior to arrival at the airport, do you send out any communications relating to physical distancing measures passengers will experience once they arrive? If yes, please describe.

website	14
Social media/email lists	11
Other media, radio commercials	3
Newsletters	1
Airport app	1
Airport has NO direct access to customers, only airlines do communication/ no communication	13
Communications by airline	2

At the airport, do you send out any communications relating to physical distancing requirements passengers are expected to observe? If yes, please describe.

Signage	20
Verbal Announcements	15
Contactless door opening	1

Highlights I.1:

- Most airports use signage as a measure to encourage physical distancing, combined with public verbal announcements.
- Other physical distancing measures are blocking or removing seats, done by half of the airports, and controlling capacity by cordoning-off areas.
- A few airports have ambassadors to encourage compliance with physical distancing measures.

Highlights I.2:

- During pre-departure, most airports depend on websites, social media, radio commercials, apps, and newsletters to communicate physical distancing at the terminals prior to arriving to the airport.
- Airlines have passengers contact information and can communicate risk reduction measure before they arrive into the terminal, but not the airports.
- Once passengers arrive at the terminal, signage and verbal announcements drive the communications by the airport.

QUESTION GUIDE

Have you made any changes to how curbside departure operations are handled? If yes, please describe.	
Changes	4
I.3 Departures How do you seek to manage physical distancing at check-in, baggage drop-off, TSA check, on escalators, in elevators?	
Capacity control / Workstation or kiosk separation /	8
Signage	22
Self-baggage service via QR codes	1
Barriers	6
Do you use any signage and/or announcements to support physical distancing measures? If so, please provide some examples	
Signage	22
Image provided	11
Verbal Announcements	7
I.4 Airport and Gate Experience Do you require physical distancing measures at gates, restaurants/cafes/food courts, shopping venues and/or restrooms? If yes, please describe.	
Physical distancing	15
via signage	9
Minimizing congestion and congregation	10
Barriers plexiglass	6
Food ordering via app	4
Do any of the physical distancing measures in place mean that such services are more restricted? For example, fewer seating places in restaurants. If yes, please describe.	
Restricted services (food /beverage)	20
Queue management	4

Highlights I.3:

- During departures, most of the airports depend on signage, and plexiglass barriers and capacity control strategies to manage physical distancing during passenger check-in, baggage processing, checkpoints, and vertical circulations.

Highlights I.4:

- Once the passengers are on the airport's airside spaces, physical distancing is managed through strategies minimizing congestion/congregation, by keeping appropriate distances among other passengers, as well as using contactless technologies like app ordering and online queueing.
- Almost all airports have restricted food and beverage services, and seating at terminal.
- For some airports, it pushed passengers to take off masks and eat at the gate waiting areas, where there may not be enough physical distance to other people.

Seating restrictions	8
Signage	3
Concessionaires certification / quality control	2

I.5 Arrivals

Do you have any procedure(s) in place for arriving passengers, e.g., COVID-19 information stations, health checks, registrations, sanitation stations etc.? If yes, please describe.

Additional procedures for arriving passengers	13
Signage	6
Airport (health) ambassadors	3
Self-serving stations (masks, information, sanitizer)	12
COVID testing site	1

Are any of these procedures mandated by local/state rules/regulations?

Yes	5

Are you handling baggage claim differently than in pre-COVID times? If yes, please describe.

Baggage handling different	8
Physical distancing in baggage carrousels	5

Are arrival curbside operations handled differently than in pre-COVID times? If yes, please describe.

Curbside operations handled different?	5

I.6 As more passengers return to the airport, how do you anticipate handling physical distancing?

Do you anticipate any physical modifications to your facilities?

Highlights I.5:

- Half of the airports have additional procedures for arriving passengers, and installed self-serving stations with PPE, hand sanitizer and other information. Some of the additional procedures correspond to mandates of local regulations.
- Only one airport had a COVID testing site for arriving passengers.
- Less than half of the airports handle the baggage differently, most allow for physical distancing around baggage carrousels, which are areas where people congregate to retrieve their luggage.

Highlights I.6:

- More than half of airports anticipate higher passenger volumes, and challenges to handling physical distancing at the airport facilities.
- A couple of the airports are looking into communications and technical solution to aid when physical distancing would not be possible.

QUESTION GUIDE

Physical modifications/ challenges to facilities	15
Sanitizing systems or sanitizing curtains/walkthru	1
Seating configurations	3
Signage	2
Continue programs implemented	3
Adjust traffic patterns/ passenger flows/use alternative facilities for additional capacity	2
Industry best practices monitoring	1

What other layers of protection do you foresee as necessary if physical distancing is not possible?

Communications	2
Barriers plexiglass	2
Changes for adequate physical distancing	1
Cleaning & sanitation	1
Decrease wait times for physical distancing	1
Technological solutions	3

J. Intra-Airport Transit

J.1 Does the airport include intra-airport transport, such as buses shuttling people to/from airplanes, transit between terminals, train above and/or below ground?

Any intra-airport transport	12
employee shuttles / rideshare	3
Airside buses (COBUS)	4 3 prior to pandemic, now suspended
Between-terminals shuttles	7
Parking / rideshare lot shuttles	10
Automated People Mover (APM) / train	9 1 will implement in future
Bus service inter city	1

J.2 Have you changed any of the ways you manage bus/shuttle rides, air tram/train rides, and other means of moving people?

Any changes	15 yes
Increasing number of shuttles / frequency	4
Using larger buses for social distancing	1
Suspended service	6
Shorter trips	1
Passenger crowding control / Reducing number of passengers / physical distancing / seat blocking	9
Parking management	3
Reduced number of trains / shuttles / number of stops	3
Barriers inside shuttles/trains	3
Face covering / mask requirement	3
Cleaning & disinfection (buses/trains)	4
Adjusted schedules	1

Highlights J.1:

- About half of the airports have intra-airport transport options, mostly parking shuttles, APM trains, and inter-terminals shuttles.

Highlights J.2:

- These airports had to modify the management of intra-airport transport options, with strategies such as reducing number of passengers per vehicle, additional cleaning and disinfection, increasing the frequency of trips.

QUESTION GUIDE

J.3 Have you changed any of the ways you arrange transfers between terminals and gates given the COVID-19 situation, e.g., dedicated lanes, allowing more time between transfers?

Any changes?	4
Increased shuttle headways / train frequency	2
Adjusted number of vehicles	1

J.4 Have you implemented physical distancing measures within these intra-airport transit systems?

Any changes?	12
Reducing number passengers	5
Mask wearing	1
Barriers inside shuttles/trains	2
Increasing number of shuttles / frequency of service	3
Signage	6
Verbal announcements	3

J.5 Have you changed any of the ways you manage luggage handling and transfers?

Changes to luggage handling? Any transfers?	5
Discouraging staff to not handle passenger luggage	1
Tracking baggage	1
Maximizing physical distancing	2
Carry-on luggage	1
Increased sanitation / cleaning	2

J.6 Are there any measures to manage pedestrian (i.e., visitors who are not passengers) movements within the airport and terminals?

Any measures?	8
One-way circulation system	1
Minimize staff ridership during peak periods	1

Highlights J.3:

- A couple of airports increased shuttle headways and APM trains frequency to handle transfers between terminals.

Highlights J.4:

- About half of the airports implemented physical distancing measures in intra-airport transit systems.

Highlights J.5:

- Only a few airports changed the way luggage is handled e.g., by maximizing physical distancing on carousels or discouraging airport staff from handling passenger luggage.

Highlights J.6:

- Only few airports are adding measures to manage pedestrian movements in the airport and terminals.
- One airport encouraged staff to minimize their ridership in shuttles and trains during peak periods.

APPENDIX G

CRITICAL EVALUATION OF THE COMBINATION OF VARIOUS RISK MITIGATION STRATEGIES IN VARIOUS 'TARGET' AIRPORT SETTINGS: MONTE CARLO ANALYST

CRITICAL EVALUATION OF THE COMBINATION OF VARIOUS RISK MITIGATION STRATEGIES IN VARIOUS 'TARGET' AIRPORT SETTINGS: MONTE CARLO ANALYSIS

To provide granular information about the different aspects of the Curb-to-Curb journey it was divided into different segments:

1) Check-in area
2) Security checkpoint
3) Airport Shops
4) Eating (a) dine-in restaurants, b) fast-food restaurants/food courts, etc.)
5) Boarding gates

For each of these segments, an evaluation of an assumed **base-case**, an **enhanced-case** and **augmented-case** scenarios were determined, with the conditions for each scenario described. The base-case as described here will generally represent the conditions that existed in these segments at airport terminal buildings *prior* to airports putting in place the different NPIs to respond to the COVID-19 pandemic. The enhanced-case scenario largely represents the application of a set of NPIs relatively typical of those being employed by airports in response to the current pandemic. The augmented-case scenario represents maximally applied NPI under optimal conditions unlikely to be achievable over time in a real-world setting. However, presenting the enhanced and augmented cases is intended to help illustrate the situation airports may face in considering the relative effectiveness of applying an array of NPIs in various areas of an airport, taking into account that variations within and among airports may make certain NPIs more practicable and effective in certain settings than others.

GENERATION OF MEAN VALUES AND UNCERTAINTY FACTORS USED IN MONTE CARLO ANALYSIS FOR COVID-19 PREVENTION TECHNOLOGIES AND PRACTICES

In a Monte Carlo Analysis, a point would be drawn at random for each statistical distribution for a protective layer and will be added to other forms of protection also drawn from statistical functions to estimate an overall reduction in risk for that particular statistical simulation. The random draw of a possibility within the statistical functions for each protective layer is repeated 5,000 times in the Monte Carlo analysis performed here to get a wide range of scenarios and to get a final statistical distribution created by the permutation of different possibilities for each layer (variations in the effectiveness of health-self assessments, body temperature screening, enhanced disinfection, face mask use, etc.). The average statistical protection provided for each scenario as well as the 5^{th} and 95^{th} percentiles will be reported to compare different policy or technology options. A common practice for scientific estimations and field data is to report mean values for input and output parameters. Most of the time a measure of dispersion is reported for the mean values to include uncertainty. There are several components of uncertainty in a scientific or technical analysis. These include:

- **Variability and stochastic error:** The values describing inputs and outputs due to measurement uncertainties, process specific variations, temporal variations, etc.
- **Appropriateness of the input or output flows:** An input or output might not perfectly match with the input or output observed in reality due to temporal and/or spatial approximations (example: The effectiveness of electrostatic spraying in the USA in 2020 might not be the same as the effectiveness of electrostatic spraying in Europe in 2020).
- **Model uncertainty:** The model used to describe the process may be inappropriate (using a linear instead of a non-linear relationship in modeling).
- **Neglecting important processes in the model:** Not all relevant information might be available to describe the process completely. These unknown inputs and outputs are missing in the scientific or technical analysis.

A method to improve data quality was used to estimate uncertainties in a technical life cycle analysis by Pedersen, Weidema and Wesnaes in 1996. This method proposes a matrix of data quality indicators and corresponding coefficients of variation, in this way the basic uncertainty of a parameter can be adjusted to reflect other sources of variation. Overall coefficient of variation is estimated by calculating the square root of the sum of the squares of the individual coefficients for each uncertainty source.

$$(1+ Cv) = \exp \left[\sqrt{([(\ln(U_1)]^2 + [(\ln(U_2)]^2 + [(\ln(U_3)]^2 + [(\ln(U_4)]^2 + [(\ln(U_5)]^2 + [(\ln(U_6)]^2 + [(\ln(U_b)]^2) } \right]$$

Where:

Cv: Coefficient of Variation

U_1: Uncertainty Factor of Reliability

U_2: Uncertainty Factor of Completeness

U_3: Uncertainty Factor of Temporal Correlation

U_4: Uncertainty Factor of Geographic Correlation

U_5: Uncertainty Factor of Technological Correlation

U_6: Uncertainty Factor of Sample Size

U_b: Basic Uncertainty Factor

Uncertainty factors are determined by applying together a matrix of data quality indicators and a table of default uncertainty factors. The matrix of data quality indicators describes qualitative characteristics for each one of the categories of uncertainty factors, descriptions are used to assign an indicator score of uncertainty. Values for uncertainty factors are determined by matching the indicator score of uncertainty from the matrix of data quality with its corresponding type of uncertainty in the table of default uncertainty factors. A larger basic uncertainty factor is applied when there is missing information in the matrix of data quality. Overall uncertainty estimations are given in a unit process level (for example, effectiveness of HEPA filters, proportion of airborne infections, etc.).

CONTRIBUTIONS FOR EACH COVID-19 PREVENTION CONTROL IN A LAYERED APPROACH UNDER DIFFERENT SCENARIOS

In a layered approach for COVID-19 prevention, the order in which controls are applied matters, therefore the contribution to overall protection from each layer might be different depending on which controls were applied previously. For example, the protection contribution of universal cloth facemask wearing in an airport without any previous control measures is around 87.5%, but that would change to 69.45% if self-health attestations are used for all passengers before coming to the airport as the first applied layer of protection is likely to reduce infected people by 20.62% (Chapter 4). In this case, the effectiveness of universal cloth face mask wearing remains the same, but it is applied to just 79.38% of the background cases in the community due to the reduction achieved by the first layer of protection (79.38% x 87.5% = 69.45%). The reason to show the prevention contribution by each SARS-CoV-2 risk mitigation layer is to illustrate how subsequent controls are affected by early controls which might be helpful when selecting particular protection strategies for every site (for example, measuring body temperature is labor intensive and not very effective, so efforts might be better used in enforcing mask wearing and in increasing ventilation).

Check-in

Check-in Using Base-Case Scenario.

In this scenario, the baseline protections before COVID-19 are regular surface disinfection, standard ventilation and MERV 8 filters in a large room with high ceilings.

Table G.1 COVID-19 Prevention Contributions For Check-In Using A Base-Case Scenario Within An Airport

Type of Space	Room with high ceiling (>14 feet/4.3 meters)	Contribution to overall protection
Level of intervention	**SARS-CoV-2 area of intervention**	
None	Self-health attestation at home when checking-in	0.00%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
None	Personal protection (e.g. face masks)	0.00%
Regular surface disinfection with EPA Cleaners	Surface disinfection	10.00%
Standard building ventilation conditions	Ventilation	40.61%
MERV 8 Filters	Air filters	10.87%
None	Physical distancing Physical distancing signage and crowd control	0.00%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**61.48%**

Check-in Using Enhanced-Case Scenario

In this scenario, health attestations are undertaken, all people wear non-surgical cloth face masks, there is enhanced surface disinfection, good ventilation and MERV 13 air filters.

Table G.2 COVID-19 Prevention Contributions For Check-In Using Enhanced-Case Scenario Within An Airport

Type of Space	Room with high ceiling (>14 feet/4.3 meters)	Contribution to overall protection
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
All people wear non-surgical cloth masks all the time (from silk to cotton mix)	Personal protection (e.g. face masks)	69.46%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	1.49%
Good building ventilation conditions	Ventilation	8.43%
MERV 13 Filters	Air filters	0.00%
Yes	Physical distancing Physical distancing signage and crowd control	0.00%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**100.00%**

Check-in Using Augmented-Case Scenario

In this scenario, health attestations are undertaken, there is COVID-19 rapid testing, all individuals wear non-surgical cloth masks, there is enhanced surface disinfection, good ventilation, MERV13 air filters, to maintain physical distancing, physical barriers are in places in the check-in area and Contactless technologies are in place.

Table G.3 COVID-19 Prevention Contributions For Check-In Using Augmented-Case Scenario Within An Airport.		
Type of Space	Room with high ceiling (>14 feet/4.3 meters)	Contribution to overall protection
Level of intervention	SARS-CoV-2 area of intervention	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
Rapid Testing Onsite	COVID-19 testing	71.55%
All people wear non-surgical cloth masks all the time (from silk to cotton mix)	Personal protection (e.g. face masks)	6.85%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	0.15%
Good building ventilation conditions	Ventilation	0.83%
MERV 13 Filters	Air filters	0.00%
Yes	Physical distancing Physical distancing Physical distancing signage and crowd control	0.00%
Yes	Physical barriers (e.g. plexiglass)	0.00%
Yes	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**100.00%**

Security Checkpoint

Security Checkpoint Using Base-Case Scenario

In this scenario, there is regular surface disinfection, standard ventilation, and MERV8 air filters.

Table G.4 COVID-19 Prevention Contributions For The Security Checkpoint Using A Base-Case Scenario Within An Airport.		
Type of Space	Room with medium height ceiling (8-14 feet/2.4-4.3 meters)	Contribution to overall protection
Level of intervention	COVID-19 area of SARS-CoV-2 area of intervention	
None	Self-health attestation at home when checking-in	0.00%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
None	Personal protection (e.g., face masks)	0.00%
Regular surface disinfection with EPA Cleaners	Surface disinfection	10.00%
Standard building ventilation conditions	Ventilation	32.49%
MERV 8 Filters	Air filters	12.65%
None	Physical distancing signage and crowd control	0.00%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**55.14%**

Security Checkpoint Using Enhanced-Case Scenario

In this scenario, there is pre-health screening, all individuals wear a non-surgical cloth mask, with enhanced surface disinfection, good ventilation, MERV13 air filters, with signage to maintain physical distancing and physical barriers for officers in the security area.

Table G.5 COVID-19 Prevention Contributions For The Security Area Using An Enhanced-Case Scenario Within An Airport

Type of Space	**Room with medium height ceiling (8-14 feet/2.4-4.3 meters)**	**Contribution to overall protection**
Level of intervention	**COVID-19 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
All people wear non-surgical cloth masks all the time (from silk to cotton mix)	Personal protection (e.g., face masks)	69.46%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	1.49%
Good building ventilation conditions	Ventilation	6.75%
MERV 13 Filters	Air filters	0.61%
Yes	Physical distancing signage and crowd control	0.22%
Yes	Physical barriers (e.g., plexiglass)	0.12%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**99.26%**

Security Checkpoint Using An Augmented-Case Scenario

In this scenario, there is health attestation, onsite rapid testing, all individuals wear non-surgical cloth masks, surface disinfection is enhanced, there is good ventilation, MERV13 air filters are fitted, physical distancing is present, physical barriers in the security checkpoint area are in place, with contactless technologies.

Table G.6 COVID-19 Prevention Contributions For The Security Checkpoint Using An Augmented-Case Scenario Within An Airport		
Type of Space	**Room with medium height ceiling (8-14 feet/2.4-4.3 meters)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
Rapid Testing Onsite	COVID-19 testing	71.56%
All people wear non-surgical cloth masks all the time (from silk to cotton mix)	Personal protection (e.g. face masks)	6.85%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	0.15%
Good building ventilation conditions	Ventilation	0.67%
MERV 13 Filters	Air filters	0.06%
Yes	Physical distancing signage and crowd control	0.02%
Yes	Physical barriers (e.g. plexiglass)	0.01%
Yes	Contactless technologies	0.01%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**99.93%**

The augmented scenario only provides a 0.67% added protection when compared to the enhanced scenario; these are just marginal gains while requiring significant labor and capital investments.

Airport Shops

Airport Shops Using Base-Case Scenario

In this scenario, there is regular surface disinfection, standard ventilation, MERV8 air filters and contactless technologies for payments.

Table G.7 COVID-19 Prevention Contributions For Airport Shops Using A Base-Case Scenario Within An Airport.		
Type of Space	**Room with low ceiling (8 feet/2.4 meters or less)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
None	Self-health attestation at home when checking-in	0.00%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
None	Personal protection (e.g. face masks)	0.00%
Regular surface disinfection with EPA Cleaners	Surface disinfection	10.00%
Standard building ventilation conditions	Ventilation	24.37%
MERV 8 Filters	Air filters	14.44%
None	Physical distancing signage and crowd control	0.00%
None	Physical barriers (e.g. plexiglass)	0.00%
Contactless technologies	Contactless technologies	5.53%
No antimicrobial coatings or materials	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**54.33%**

Airport Shops Using Enhanced-Case Scenario

In this scenario, there is health attestation, all individuals wear a non-surgical cloth mask, there is enhanced surface disinfection, good ventilation, MERV13 air filters, signage to maintain physical distancing and contactless technologies for payments.

Table G.8 COVID-19 Prevention Contributions For Airport Shops Using An Enhanced-Case Scenario Within An Airport.

Type of Space	Room with low ceiling (8 feet/2.4 meters or less)	Contribution to overall protection
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
All people wear non-surgical cloth masks all the time (from silk to cotton mix)	Personal protection (e.g. face masks)	69.46%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	1.49%
Good building ventilation conditions	Ventilation	5.06%
MERV 13 Filters	Air filters	1.21%
Yes	Physical distancing signage and crowd control	0.44%
None	Physical barriers (e.g. plexiglass)	0.00%
Contactless technologies	Contactless technologies	0.19%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**98.46%**

Airport Shops Using Augmented-Case Scenario

In this scenario, there is health attestation, COVID-19 rapid testing onsite, all individuals wear non-surgical cloth masks, there is enhanced surface disinfection, good ventilation, high ceilings, MERV13 filters, to maintain physical distancing is in place, physical barriers for cashiers are installed and Contactless technologies for payments are in place.

Table G.9 COVID-19 Prevention Contributions For Airport Shops Using An Augmented-Case Scenario Within An Airport		
Type of Space	**Room with low ceiling (8 feet/2.4 meters or less)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
Rapid Testing Onsite	COVID-19 testing	71.55%
All people wear non-surgical cloth masks all the time (from silk to cotton mix)	Personal protection (e.g. face masks)	6.85%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	0.15%
Good building ventilation conditions	Ventilation	0.50%
MERV 13 Filters	Air filters	0.12%
Yes	Physical distancing signage and crowd control	0.04%
Yes	Physical barriers (e.g. plexiglass)	0.02%
Yes	Contactless technologies	0.02%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**99.87%**

Eating

Eating In A Restaurant (Dining-In) Using Base-Case Scenario

In this scenario, there is regular surface disinfection, standard ventilation and MERV8 air filters (a restaurant with medium-height ceilings is assumed).

Table G.10 COVID-19 Prevention Contributions For Eating In A Restaurant (Dining-In) Using A Base-Case Scenario Within An Airport.		
Type of Space	**Room with medium height ceiling (8-14 feet/2.4-4.3 meters)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
None	Self-health attestation at home when checking-in	0.00%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
None	Personal protection (e.g. face masks)	0.00%
Regular surface disinfection with EPA Cleaners	Surface disinfection	10.00%
Standard building ventilation conditions	Ventilation	32.49%
MERV 8 Filters	Air filters	12.65%
None	Physical distancing signage and crowd control	0.00%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**55.14%**

Eating In A Restaurant (Dining-In) Using Enhanced-Case Scenario

In this scenario, health attestation is undertaken, some individuals wear a non-surgical cloth mask around people eating, enhanced surface disinfection, standard ventilation, building with medium-height ceilings, MERV13 filters and barriers are in place to maintain physical distancing.

Table G.11 COVID-19 Prevention Contributions For Eating Using An Enhanced-Case Scenario Within An Airport

Type of Space	Room with medium height ceiling (8-14 feet/2.4-4.3 meters)	Contribution to overall protection
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
An individual wears a non-surgical cloth mask	Personal protection (e.g. face masks)	52.39%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	4.05%
Good building ventilation conditions	Ventilation	18.35%
MERV 13 Filters	Air filters	1.65%
Yes	Physical distancing signage and crowd control	0.59%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**97.66%**

Eating In A Restaurant (Dining-In) Using Augmented-Case Scenario

In this scenario, there is health attestation, rapid COVID-19 testing onsite, most people around eaters are wearing a non-surgical cloth mask, surface disinfection is enhanced, ventilation is good, ceilings height is medium (8 to 14 ft height), with MERV13 air filters, to maintain physical distancing is in place, physical barriers for cashiers are installed and contactless technologies are in use with antimicrobial materials on tables.

Table G.12 COVID-19 Prevention Contributions For Eating In A Restaurant (Dining-In) Using An Augmented-Case Scenario Within An Airport		
Type of Space	**Room with medium height ceiling (8-14 feet/2.4-4.3 meters)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
Rapid Testing Onsite	COVID-19 testing	71.55%
An individual wears a non-surgical cloth mask	Personal protection (e.g. face masks)	5.17%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	0.40%
Good building ventilation conditions	Ventilation	1.81%
MERV 13 Filters	Air filters	0.16%
Yes	Physical distancing signage and crowd control	0.06%
Yes	Physical barriers (e.g. plexiglass)	0.03%
Yes	Contactless technologies	0.02%
Yes	Antimicrobial Coatings and materials	0.02%
	Average overall protection	**99.84%**

There is a 2.18% added protection from an augmented scenario when compared to the enhanced scenario, this should be considered when investing in labor, testing and capital investments in an airport restaurant.

Eating In A Food Court Using Base-Case Scenario

In this scenario, there is regular surface disinfection, standard ventilation and MERV8 air filters (a food court with high ceilings is assumed).

Table G.13 COVID-19 Prevention Contributions For Eating In A Food Court Using A Base-Case Scenario Within An Airport		
Type of Space	**Room with high ceiling (>14 feet/4.3 meters)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
None	Self-health attestation at home when checking-in	0.00%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
None	Personal protection (e.g. face masks)	0.00%
Regular surface disinfection with EPA Cleaners	Surface disinfection	10.00%
Standard building ventilation conditions	Ventilation	40.61%
MERV 8 Filters	Air filters	10.87%
None	Physical distancing signage and crowd control	0.00%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**61.48%**

Eating In A Food Court Using Enhanced-Case Scenario

In this scenario, health attestation is undertaken, some individuals wear a non-surgical cloth mask around people eating, enhanced surface disinfection, standard ventilation, ceilings are high because a food court is assumed, MERV13 filters and no barriers are in place to maintain physical distancing.

Table G.14 COVID-19 Prevention Contributions For Eating Using An Enhanced-Case Scenario Within An Airport

Type of Space	Room with high ceiling (>14 feet/4.3 meters)	Contribution to overall protection
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
An individual wears a non-surgical cloth mask	Personal protection (e.g. face masks)	52.39%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	4.05%
Good building ventilation conditions	Ventilation	22.94%
MERV 13 Filters	Air filters	0.00%
Yes	Physical distancing signage and crowd control	0.00%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**100.00%**

Eating Using Augmented-Case Scenario

In this scenario, there is health attestation, rapid COVID-19 testing onsite, most people around eaters are wearing a non-surgical cloth mask, surface disinfection is enhanced, ventilation is good, ceilings are high (a food court is assumed), with MERV13 air filters, to maintain physical distancing is in place, physical barriers for cashiers are installed and Contactless technologies are in use with antimicrobial materials on tables.

Table G.15 COVID-19 Prevention Contributions For Eating Using An Augmented-Case Scenario Within An Airport		
Type of Space	**Room with high ceiling (>14 feet/4.3 meters)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
Rapid Testing Onsite	COVID-19 testing	71.55%
An individual wears a non-surgical cloth mask	Personal protection (e.g. face masks)	5.17%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	0.40%
Good building ventilation conditions	Ventilation	2.26%
MERV 13 Filters	Air filters	0.00%
Yes	Physical distancing signage and crowd control	0.00%
Yes	Physical barriers (e.g. plexiglass)	0.00%
Yes	Contactless technologies	0.00%
Yes	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**100.00%**

There is no difference in protection between the enhanced and augmented scenarios, this should be considered before investing in labor and retrofits in an airport food court.

Boarding Gates

Boarding Gates Using Base-Case Scenario

In this scenario, there is poor surface disinfection due to high occupancy in wait areas, standard ventilation rand MERV8 air filters.

Table G.16 COVID-19 Prevention Contributions For Boarding Gates Using A Base-Case Scenario Within An Airport		
Type of Space	**Room with medium height ceiling (8-14 feet/2.4-4.3 meters)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
None	Self-health attestation at home when checking-in	0.00%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
None	Personal protection (e.g. face masks)	0.00%
Poor surface disinfection	Surface disinfection	5.00%
Standard building ventilation conditions	Ventilation	34.30%
MERV 8 Filters	Air filters	13.36%
None	Physical distancing signage and crowd control	0.00%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**52.65%**

Boarding Gates Using Enhanced Case Scenario

In this scenario, there is health attestation, all individuals wear a non-surgical cloth mask, regular surface disinfection due to constant high occupancy, enhanced ventilation, MERV13 air filters and barrier are installed to maintain physical distancing is in place.

Table G.17 COVID-19 Prevention Contributions For Boarding Gates Using An Enhanced-Case Scenario Within An Airport

Type of Space	Room with medium height ceiling (8-14 feet/2.4-4.3 meters)	Contribution to overall protection
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
None	Symptom screening	0.00%
None	COVID-19 testing	0.00%
All people wear non-surgical cloth masks all the time (from silk to cotton mix)	Personal protection (e.g. face masks)	69.46%
Regular surface disinfection with EPA Cleaners	Surface disinfection	0.99%
Good building ventilation conditions	Ventilation	7.14%
MERV 13 Filters	Air filters	0.64%
Yes	Physical distancing signage and crowd control	0.23%
None	Physical barriers (e.g. plexiglass)	0.00%
None	Contactless technologies	0.00%
None	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**99.09%**

Boarding Gates Using Augmented-Case Scenario

In this scenario, there is health attestation, rapid COVID-19 testing onsite, all individuals wear a non-surgical cloth mask, surface disinfection is enhanced, ventilation is good, MERV13 air filters, to maintain physical distancing is in place, physical barriers for airline employees and contactless technologies are installed and in use.

Table G.18 COVID-19 Prevention Contributions For Boarding Gates Using An Augmented-Case Scenario Within An Airport		
Type of Space	**Room with medium height ceiling (8-14 feet/2.4-4.3 meters)**	**Contribution to overall protection**
Level of intervention	**SARS-CoV-2 area of intervention**	
Yes	Self-health attestation at home when checking-in	20.62%
No	Symptom screening	0.00%
Rapid Testing Onsite	COVID-19 testing	71.55%
All people wear non-surgical cloth masks all the time (from silk to cotton mix)	Personal protection (e.g. face masks)	6.85%
Enhanced surface disinfection with EPA Cleaning Agents	Surface disinfection	0.15%
Good building ventilation conditions	Ventilation	0.67%
MERV 13 Filters	Air filters	0.06%
Yes	Physical distancing signage and crowd control	0.02%
Yes	Physical barriers (e.g. plexiglass)	0.01%
Yes	Contactless technologies	0.01%
Yes	Antimicrobial Coatings and materials	0.00%
	Average overall protection	**99.93%**

APPENDIX H

QUANTA

QUANTA

As with almost all other respiratory airborne infectious pathogens, there is still limited understanding of what constitutes an infectious dose for a COVID-19 case. Previous studies of SARS-CoV-1 and human common cold coronaviruses suggest that the infectious dose capable of causing disease in 50% of the population (ID50) is approximately 280 viral particles (Watanabe et al., 2010). To date, the infectious dose for COVID-19 has not been determined. Therefore, aerosol science researchers have for many years attempted to bridge this gap in knowledge by using the concept of 'quanta'.

William Wells introduced the term quanta to represent the minimum dose of airborne organisms necessary to cause infection in the host. For pathogens transmitted via the aerosol route, an infectious dose can be defined by an infectious quanta emission rate (quanta per hour). Wells postulated that not all inhaled particles containing respiratory aerosols would result in infection and therefore defined a quantum of infection as the number of infectious respiratory aerosols required to infect 63% of susceptible people (Wells, 1955). Based on the concept of quanta, an equation was developed, the Wells-Riley equation (Riley et al., 1978). The equation is used to assess the probability of infection of a susceptible population where factors relevant to transmission are understood – such as the length of exposure, ventilation rate in the indoor space, and the pulmonary ventilation rate of susceptible individuals. The Wells-Riley approach does however have limitations. For example, the model assumes air is well mixed, such that quanta are evenly distributed in the spaces shared by an infectious person and susceptible hosts. Applying the Wells-Riley model when case and host are in close proximity may underestimate transmission depending on how rapidly viral emissions are dispersed.

Quanta emission rates are calculated typically based on a retrospective review of a transmission event, where factors relevant to transmission (e.g., length of exposure, conditions of the space) are reasonably well known. Essentially, the quanta concept approaches the study of transmission retrospectively from the result, namely the infection rates, rather than prospectively based on particle numbers or even culturable virus concentrations. The quanta emission rate can be dependent on a number of factors, including the amount of aerosol generated by specific activities (e.g., breathing, standing, singing, exercise) and the infectious state of the infector (e.g., asymptomatic, pre-symptomatic, symptomatic). The concept of quanta and the Wells-Riley equation are used extensively in analyzing ventilation strategy and its association to airborne infections in clinical environments (Nardell et al., 1991; Fennelly & Nardell, 1998; Escombe et al., 2007).

Several studies have estimated quanta emission rates of SARS-CoV-2. Buonanno and colleagues (Buonanno et al., 2020a; Bounanno et al., 2020b) estimated quanta emission rates for activities, including resting, oral breathing (0.36 quanta/hr), heavy activity (oral breathing, 2.4 quanta/hr), speaking with light activity (4.9 quanta/hr), and singing or speaking loudly (31 quanta/hr)

(Buonanno et al., 2020a; Buonanno et al., 2020b). Other investigators have estimated quanta emission rates for specific outbreaks. Hota et al. (2020) calculated an emission rate based in the healthcare setting of 0.225 quanta/hr, which is consistent with the value mentioned for resting activities. Miller et al. (2020) calculated a very high emission rate of 970 quanta/hr for singing loudly based on a super-spreader outbreak that occurred at a chorus rehearsal where 53 members of the group were confirmed or strongly suspected of having contracted COVID-19. Recent studies have estimated emission rates ranging from two quanta per hour (breathing at rest) to 970 quanta per hour (singing) (Buonanno et al., 2020a; Bounanno et al., 2020b; Miller et al., 2020). As the estimates of quanta emissions are generally based on retrospective reviews of transmission events, the results are consistent with other available scientific evidence, such as the studies that report higher generation of particles when speaking loudly. Additionally, the SARS-CoV-2 estimates are reasonable give quanta values reported for other infectious disease (e.g., SARS-CoV-1: 28 q/h; influenza: 15-128 q/h; measles 5,580 q/h) (Riley, 1978; Liao et al., 2005; Knibbs et al., 2012).

Several important factors influence the infectivity of aerosols. For example, each droplet or respiratory particle may not carry one or more infectious virions in it. Importantly, one copy of RNA does not represent one viable infectious virus, much less one quantum (successful infection). If that were the case, it would assume infection would occur for each pathogen (RNA copy, in the case of SARS-CoV-2) received by the exposed people. Therefore, researchers have introduced a conversion factor, ci, defined as the ratio between one infectious quantum and the infectious dose expressed in viral RNA copies. The conversion factor for SARS-CoV-2 is unknown; however, studies with other coronaviruses have estimated that value to be somewhere between 0.01 and 0.1 (Buonanno et al., 2020a; Bounanno et al., 2020b).

Estimating infectious dose is useful for comparing pathogens as being more or less infectious, but any estimate is based on many assumptions. A viral dose assumes airborne viruses are uniformly infectious across all conditions, whereas influenza, for example, appears to be more infectious in conditions of low absolute humidity (Lowen & Steel, 2014). It also assumes average host susceptibility, but differences in innate, learned, and adaptive immunity among individuals and populations are well known (Lowen & Steel, 2014). For mathematical models of infection, modelers often estimate source strength and infectious dose – although Wells' quanta concept remains a useful way to model transmission without committing to an actual dose number.

Particles (detectable, viable, and infectious) are estimated from source measurements, but include many particles that do not cause infection due to viability, infectivity, host defenses, etc. Quanta are agnostic about the actual number of particles but quantifies the number of doses generated by the source under specific circumstances and considering the probability of inhaling an infectious dose.

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APPENDIX I

MULTI-COMPARTMENT MARKOV CHAIN MODEL

MULTI-COMPARTMENT MARKOV CHAIN MODEL

To gain insight at the near-field (NF) risk of airborne transmission SARS-CoV-2 in different airport spaces, a three-dimensional multi-compartment approach was developed and simulated the contaminant transport (i.e., infectious aerosol) by a Markov model. The multi-zone, Markov approach is well-documented in the occupational hygiene literature (Nicas 2000; Jones et al., 2009; Chen et al., 2015) and has been used extensively given its flexibility in modeling NF and far-field (FF) zone contaminants, allowing a more refined account of the variability in concentrations at a certain position and time within an enclosed space.

The main goal of the NF model was to estimate the concentrations at a 2 m distance from the emission zone and at the breathing height of a standing person (1 to 2 m above the floor). Using a series of parametric variations (Table I.1), the result is a range of adjustment factors to be used in combination with the FF models that are more ubiquitous and easier to configure for the general user.

Table I.1 Input Parameters for the Multi-Zone Models

Parameter	Values
Air exchange rate (1/h)	Range 3-6 ACH
Advective flow (m/s)	Range= 0.05 -0.2m/s
Turbulent intensity	Range = 0.1 – 0.2
Quanta rate (q/h)	100
Grid size	Height=1.0m; width=1.0m; depth=1.0m

TECHNICAL APPROACH

In summary, the model divides a given airport space in two different zone types. The NF zone is comprised of a 75 m^3 volume (width=5 m, depth=5 m, height=3 m), divided in 75 compartments of 1m^3 each. These dimensions were chosen to obtain concentration values at a 1 m resolution for at least 5 m away from the emission. The FF consists of the remaining room volume and is split in five volumes adjacent to each of the four sides and the top of the NF zone. This model setup balances the flexibility of using different space configurations while keeping computational demands low.

In a discrete time-step delta T, the probability that a particle stays in the same volume or transitions to a physically contiguous zone is determined by the magnitude of each of the mass transport mechanisms present in the room, such as exhaust ventilation, advective velocity and turbulent diffusion. For the advective velocity, a mean air velocity u between 0.05 m/s and 0.2 m/s was considered. For the turbulent diffusion term u', the following equation derived from the K diffusivity theory was used:

$$u' = \sigma_u \quad L_{x/d\ x}$$

where σ_u is the standard deviation of turbulence fluctuations, Lx is turbulence scale length (depending on the room size), and dx is the length of the compartment box. A turbulence intensity range between 0.1 to 0.2, was used multiplied by the mean air velocity u equals σ_u. Gravitational and virus inactivation first-order constants were not considered due to the predominance of the aforementioned removal mechanisms. These probabilities are arranged in a matrix of NxN dimensions, known as the one-step transition probability matrix P. This matrix contains all the information about the probabilities of particles released at any zone to enter an adjacent zone. By recursively multiplying P by itself n times, an estimate of the probability that a particle is still in the room at the n^{th} step is determined. For example, the expected concentration at time t at a zone corresponding to the i^{th} row and j^{th} column of P is:

$$E(C_{(i,j)}(t)) = (N_0 \times 〚P_{(i,j)}〛^t)/V$$

where N0/V is the initial particle concentration at time zero. A total of 80 zones are included in the model, two of which are described as absorbing zones or states, corresponding to the exhaust located 7 meters away from the emission zone at a 3m height.

Table I.2 shows the model results of NF to FF concentration ratios (NF/FF) for different advective flow and turbulence intensity inputs. The model considers a continuous quanta emission rate of 100 q/hr and the concentrations are modeled at a 1-second time step for a total duration of 3600s. The NF/FF values range from 2.0-5.7 for the evaluated scenarios. Increases in advective flow and turbulence intensity levels result in a more effective dispersion of the emissions close to the source.

Table I.2 Near-Field (NF) to Far-Field (FF) Concentration Ratio Results from Multi-Zone Model

Advective speed [m/s]	Air exchange rate [h^{-1}]	Turbulence intensity	NF/FF Ratio
0.05	3	0.1	5.7
0.05	3	0.15	4.8
0.05	3	0.2	4.3
0.1	3	0.1	4.4
0.1	3	0.15	3.5
0.1	3	0.2	3.0
2	3	0.1	3.0
2	3	0.15	2.3
2	3	0.2	2.0

Near-Field using a basic Transport and Dispersion (T&D) model

Due to the greater relative importance of the NF exposures, especially at densely occupied spaces such as boarding gates, and the potential longer exposure duration (e.g. during a flight delay), the computed concentrations were compared for an additional scenario, where the 'infector' eats at some random location in the boarding gate without using a mask. As a worst-case scenario, it was assumed that the infector generates an undisturbed plume at a constant emission rate creating a high-concentration field resulting from the exhalation momentum out of the mouth and/or nose. A simple transport and dispersion basic model (Hanna, 2020) estimates the concentration at a distance x from the emitter as a function of the emission rate, air velocity and turbulence intensity, as shown:

$$C = \frac{Q_c}{u \times (D_0 + 0.1x)^2}$$

Where Q_c is the emission rate, D_0 is the initial side dimension of an assumed cube-shaped plume centered at the height of the infector's mouth, u is the mean flow air speed, and 0.1 corresponds to turbulence intensity (ratio of turbulent velocity to mean velocity). Using this model with u=0.1 m/s (same as in the multizone models), the average concentration in the plume at less than **2 m from the emitter can be between 40 (for D_0=0.5 m) and 175 (for D_0=0.2 m) times** larger than the FF concentration estimated by the single-zone model. Those high concentration fields could lead in the order of minutes to equivalent risk levels for a multi-hour (Table I.3).

Table I.3 Input Parameters for the Single-Zone, Well Mixed Models

Space Type	Exposure Duration [min]	Area [m]	Base Case Ceiling Height [m]	Base Case Air Exchange Rate [h^{-1}]	Quanta Emission Rate [q/hr]	Number of Assumed Infectors in the Space	Virus Infectivity Decay [h^{-1}]	Deposition Rate [h^{-1}]
Shuttle to Airport	20	13.5	2	58	100	1	0.32	0.3
Flight Check-in	20	20.0	4	3	100	1	0.32	0.3
Security Checkpoint	40	1555.5	4	3	100	1	0.32	0.3
Terminal train	20	23.3	2.3	58	100	1	0.32	0.3
Boarding Gate; Large International Airport	60 (40 waiting +20 queuing)	250.0	4	3	100	1	0.32	0.3
Boarding Gate; Small Regional Airport	50 (40 waiting +10 queuing)	150.0	3	3	100	1	0.32	0.3
Bus to Plane	10	29.1	2.4	58	100	1	0.32	0.3

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APPENDIX J

COMPUTATIONAL FLUID DYNAMICS (CFD) SETUP

COMPUTATIONAL FLUID DYNAMICS (CFD) SETUP

The realizable k-ε model was applied with the SIMPLE algorithm. The Boussinesq assumption was used for the buoyancy force on convective flows around the surfaces. For the spatial discretization, PRESTO! was used for pressure, with first-order upwind for passive scalar, and second-order upwind for other terms. The convergence criteria were 5×10^{-4} for continuity, velocities, and turbulent terms, 1×10^{-6} for energy, and 1×10^{-14} for the scaler that represents exhaled bioaerosol attached with SARS-CoV-2.

The boundary conditions are listed in Table J.1. The temperatures for windows, windshield, floor, lights, and human body sections were derived from previous studies (Zhu et al., 2010; Zhu et al., 2012). For a terminal train, which usually runs in an indoor environment, the window and floor surfaces were taken to be adiabatic. After the source was determined, the human body's mouth opening would be set as an inlet. To calculate the velocity for exhaled air, the driver was assumed to have a metabolic rate of 1.8 met with a breathing rate of 14 l/min, and a passenger was assumed to be in a relatively quiet state with a metabolic rate of 1 met with a breathing rate of 8 l/min (Dai & Zhao, 2020).

Table J.1 Boundary Conditions

Boundary	Bus	Shuttle	Terminal train
Inlet	Area: 0.548 m^2; Vel: 2.055 m/s; T: 20.2°C	Area: 0.149 m^2; Vel: 2.981 m/s; T: 20.2°C	Area: 1.153 m^2; Vel: 0.76 m/s; T: 20.2°C
Outlet	Free Slip		
Light	No slip; T: 25°C		
Window	No slip; 16.8°C	No slip; adiabatic	
Windshield	N/A	No slip; 31.8°C	No slip; adiabatic
Seated Human Body	No slip; 23°C for legs, 24°C for trunk, 28°C for head, 30°C for feet & thighs, 34°C for face & hands		
Standing Human Body	No slip; 24°C for legs, thighs & trunk, 28°C for head, 30°C for feet, 33.5 °C for face, 34°C for hands		
Mouth of Source	Area: 0.0003 m^2; Vel: 1.07 m/s for passenger and 1.87 m/s for driver; T: 34°C		
Other Walls	No slip; adiabatic		

As the Wells-Riley equation (Riley et al., 1978; Wells, 1995) was used to estimate the infection risk, this study used quanta as infectious particles attached with SARS-CoV-2. Quantum generation rate of SARS-CoV-2 is estimated to in the range of 14~48 quanta/hr (Dai et al., 2020). Considering the existence of highly infectious individuals, often termed 'superspreader, the predicted infection risk used three quantum generation rates, i.e., 14 quanta/hr, 48 quanta/hr, and 100 quanta/hr. The spread of infectious particles was calculated using the drift-flux (Holmberg & Li, 1998) model with an active scalar, which can account for the influence of the particles' weight by adding a settling velocity vector of particles into the convective term of the scalar transport equation. The settling velocity vector is calculated using the density and particle size with Stokes law. In the simulations, this study assumed that the infectious particles had an aerodynamics diameter of 5 µm, and ignored the influence of indoor humidity and temperature on particle size, and the deposition of particles on the solid surfaces.

REGRESSION MODELING FOR ASSESSING OCCUPANCY'S IMPACT ON INFECTION RISK

In this study, the regression models was created to estimate the far-field (FF)and near-field (NF) aerosol infection risk due to the exposure to SARS-CoV-2 in the airport transportation vehicles, which are specified to address the impact of occupant density.

$$r = \delta r_{pm} \quad (7.5.1)$$

$$\delta = a e^{b \cdot \rho} \quad (7.5.2)$$

$$r_{pm} = 1 - e^{-C_{pm} q t} \quad (7.5.3)$$

Where, δ is defined as the imperfect mixing degree; r_{pm} is the infection risk under perfect mixing conditions; ρ is the occupant density [#/m^2], calculated as the number of people per unit floor area; C_{pm} is the perfect mixing concentration [quanta/m^3]; q is the breathing rate [m^3/min], which is 0.008 m^3/min; t is time [min]; and a, b are coefficients of regression models.

According to the above definition, δ demonstrates the impact of occupant density on indoor air mixing and the spread of infectious particles. It can be obtained by dividing the CFD calculated infection risk by the infection risk under perfect mixing condition. In this investigation, the breathing zone was defined as the region between the heights of 1.1 m and 1.8 m above the floor. Based on the CFD results of quantum concentration distribution, by Eq. 7.5.1, the volume-weighted average concentration of SARS-CoV-2 quantum in the breathing zone was used throughout the whole indoor space to calculate FF infection risk, and the volume-weighted average concentration in the breathing zone within the distance of 0.9 m (3 ft) to the source person, to calculate the NF infection risk.

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APPENDIX K

MODELS RELEVANT TO ASSESSING SARS-CoV-2 TRANSMISSION RISK AT AIRPORTS

MODELS RELEVANT TO ASSESSING SARS-CoV-2 TRANSMISSION RISK AT AIRPORTS

This Appendix provides a brief description of some models developed to assess indoor transmission of SARS-CoV-2. These models may be useful to inform decision-making by airport facility managers concerning ventilation strategies informed by quantitative estimates of risk reduction derived from vetted models.

The models use essentially similar approaches. In some, exhaled virus is expressed as quanta (defined as the infectious dose required to infect 63% of susceptible hosts, or as particle numbers). Other models calculate particle concentrations and deposition in respiratory tracts and then relate viral load to infection rates. Most models account for air exchange, filtration, different release rates based on talking or other activities, duration of occupancy, and breathing rates within a three-dimensionally defined space. Often it is assumed that a 'superspreader' is in the space in order to provide conservative (health protective) estimates when considering mitigation strategies. While these models rely on some of the recent science about SARS-CoV-2, assumptions about the quanta emission rates are approximations. These models were developed before the newer more infectious variant forms of the virus were identified and modifications should be considered to account for that fact.

Other models have been developed to provide guidance for specific situations like classrooms or offices. While some models are in the public domain and can be readily applied, risk assessors have developed others for commercial application and require some familiarity with mechanical ventilation systems. The more sophisticated models allow operators to alter many input variables to test various scenarios and provide comparative estimates of risk.

In deriving risk estimates from these models, the user needs to be aware of the underlying assumptions inherent in all these models. These models only simulate infection through aerosols in shared room air. Transmission by fomite contact is not considered. In most situations this limitations is not expected to change estimates of infection rate. Further, these models, derived from the Wells-Riley equation, assume a well-mixed internal environment and only consider far-field (FF) exposure. In spaces as open and complex as those found in airport terminals the assumption of a well-mixed internal environment with uniform concentration from exhaled virus is reasonable but still an approximation. The assumption is most appropriate for small spaces, but for very large spaces, the assumption of uniform concentration throughout the space becomes less reliable.

There will be areas within an airport where air mixes less well than other spaces. This, however, is not the most critical limitation for modeling airborne transmission of respiratory diseases. Given passengers are likely to be in crowded spaces at some point as they transit an airport terminal, models applied to airports would ideally incorporate near source, or near-field (NF) risk estimates. The concentrations of viruses in an exhaled breath or being expelled more forcefully by a cough or sneeze will clearly be higher near the source until mixed, diluted and dispersed uniformly in a space. Consequently, these exposures can be equal to or far greater than the exposures experienced in the FF, after dilution of the virus occurs. Hence, the common reference to ‘proper social’ or ‘physical distancing’. If passengers in a terminal could maintain an adequate separation and wear a mask to eliminate forceful discharge of a virus-laden plume, then NF exposures would be less important. At the time of writing, few models have incorporated NF considerations.

The International Society of Indoor Air Quality (ISIAQ) recently offered webinars on **Modeling Infection Risk from Indoor Aerosol Exposure to SARS-CoV-2** where developers presented their modeling approaches. Summaries of specific models that have more detail can be found on the ISIAQ website: https://www.isiaq.org/webinars.php. Since the ISIAQ Webinar, an additional COVID calculator became available. The tool, developed by researchers at MIT, models COVID-19 exposure risks in different settings and for different durations. Presented in this Appendix are abbreviated descriptions of a range of COVID models deemed more relevant to airport terminals.

COVID-19 INFECTION RISK MANAGER

Prezant, B., Ongsono, D. & Palmer, K.
Web Reference: https://vue-covid-product.web.app (description including video and white paper https://covid-risk-manager.web.app)

Short summary and assumptions: Compartment model (single zone) for calculating concentration in air, utilizes Wells-Riley for calculating risk of infection. A point estimate of risk of infection is provided in the output, as well as the number of infections arising based on the occupancy specified. The quanta (viral) emission rates are calculated for SARS-CoV-2 from various recent published research data.

It assumes perfect mixing, constant emission of quanta, that supplied air from a HVAC system is either outdoor or lacking in viral contaminant, and only one person in the room is infectious. The estimates of quanta are highly variable. For an infectious person, emission rates vary over the course on the illness and the manner, and volume of oral expression. Emission rates have been extrapolated from controlled studies and from case studies of outbreaks. Estimate of quanta emission rates range from low values while quietly breathing to between one to two orders of magnitude higher when singing, laughing or talking loudly. The model only considers longer-range airborne transmission, not virus deposited via fomites or via close transmission of less than 1-2 meters. Although the model is being modified to incorporate NF exposure for airport applications, the calculator uses the same calculations as many others. However, it was designed to operate both for scientists with specialized knowledge and trained members of the public absent specific scientific knowledge. It can therefore function as both a powerful assessment tool for a risk scientist and a risk management tool and risk communication tool for building occupants/managers.

Users such as airlines, security staff, and concessionaires can be added by the building modeler (definer), with several levels of access to view results and modify underlying assumptions. At its simplest, color codes of risk absent numbers are presented; at its most complex, all the scientific assumptions can be modified. In this manner, it adjusts to the user's technical sophistication.

In "Compare Rooms" mode applied to an airport, results for different areas can be simultaneously presented, permitting airport management to utilizations of gates, security lines and other areas of potential congestion.

In "Plan Your Activities" mode, a simulated passenger, vendor, concessionaire or employee can move through various locations of an airport, with the risk of infection summed and compared for each "activity".

For all levels of user, the model is interactive, permitting changes to be displayed in real time as input variables are changed. Depending on controlled access, these numbers include occupancy (# persons), time, speaking frequency, quanta emission rates, breathing rate, and area ventilation. This interactive version is used for sensitivity testing to bound estimates while identifying critical variables.

Relevant to an airport, where it may be difficult to acquire all the building dimensions and air exchange, the model can be run on an ad hoc basis. Carbon Dioxide (CO_2) levels can be used to infer air changes per hour (ACH).

REHVA CALCULATOR TO ESTIMATE THE EFFECT OF VENTILATION ON COVID-19 AIRBORNE TRANSMISSION.

Mazzarella, L. Department of Energy, Politecnico di Milano, Italy under AiCARR and REHVA COVID-19 Task Forces.
Web Reference: https://www.rehva.eu/covid19-ventilation-calculator

The model, offered by REHVA the Federation of European Heating, Ventilation and Air Conditioning Associations, is appropriate for several indoor environments including airports. The model should be utilized to minimize SARS-Cov-2 infection risk in buildings through operating or modifying their HVAC system in various ways including the use of supplemental air purifiers. While not a primary route for transmission, the model can be used to calculate daily virus deposition on surfaces. Through comparative analysis, airport facility managers can use the model to explore the best options and combinations that can minimize infection risk.
The tool is based on the standard airborne disease transmission Wells-Riley model, i.e. quanta based and full mix hypothesis. It extends the single room model to a Multi-rooms model with

possible air recirculation among rooms, through centralized HVAC system and via air transfer to common service areas (e.g., corridor, rest rooms and staircases) where air extraction to outside is performed via dedicated exhaust air ductwork.

This is a dynamic model, i.e. solving for the time dependent problem. As such, it might be used to assess time varying aspects found at airports as passengers gather over time in a gate holding area or the residual time where viruses might be still suspended in the air after the infectious source leaves. By incorporating a term for Contaminant Removal Effectiveness (CRE), it can simulate departure from the full-mix hypothesis. However, the judgement of a programmer familiar with the performance of ventilations systems is needed to set the CRE. While there is little or no evidence for transmission of SARS CoV-2 though air ducts, this model can adjust a removal factor for viruses in the recirculated air from one (no removal) to zero for HEPA filter or equivalent. This might be useful in local conditioned air supplied by fan coil units (VAV Boxes) serving nearby spaces. This configuration might involve little or no ductwork and low efficiency filters. In airport locations with high ceilings, upper room UV-C with mixing fans can enhance air cleaning and greatly increase the removal of viable viruses and limit them from being distributed in a space like departure lobbies.

This model allows the estimation of ventilation and “filtration” effects on SARS-CoV-2 airborne infection in a HVAC multi-zone air system with specified air recirculation among different building spaces. The model could be customized for airport applications with open floor plans.

RESET INDEX: REAL-TIME AEROSOL INFECTION ESTIMATOR

Wallis, R. & Green, A.
Web Description with video instruction: https://reset.build/resources/indexes

The RESET approach offers an index of building performance. The index breaks down and compiles data on virus survivability, the impact on immune system health, and exposure or dosage to calculate infection potential, all of which can provide insights into the outcome of operational decisions.

Less than 1% on the index means that the indoor air quality has been fully optimized and the potential for airborne infection is minimized, while 100% means that the indoor air quality is not optimized and the potential airborne infection is very high. The index provides building operators with an easy way to understand the contribution a building’s air quality system makes to the reduction of potential infection via airborne (aerosol) pathways.

Rather than assuming a steady state well-mixed indoor environment the RESET offers a real-time estimator whose results could be used to respond to IAQ concerns in real-time. As a result, the RESET Index is designed to work with real-time data measured by sensors. Limitations of the RESET model are its real time data requirements. This might not be an impediment for some airports with arrays of CO_2 sensors and a more sophisticated building management system.

SIMULATION OF SARS-COV-2 AEROSOL EMISSIONS IN THE INFECTED POPULATION AND RESULTING AIRBORNE EXPOSURES IN DIFFERENT INDOOR SCENARIOS

Riediker, M. & Monn. C.
Publication Reference: https://doi.org/10.4209/aaqr.2020.08.0531

This tool calculates the concentration of viruses in a room emitted by a person of different emission strengths (low-, medium- and super-emitter) with perfect mixing for one or more people who emit viruses while breathing normally, speaking softly or loudly and at different levels of physical exercise. The type of masks worn by the source and target can also be defined. The tool allows the calculation of scenarios where the virus carrier enters a room and stays there for a certain period of time, and what this means for exposure and inhaled dose of other people in the room. The model also provides an estimation of the NF concentrations (within 60 cm, i.e., the distance of a seat in public transport vehicles or at events).

Risk assessors, ventilation specialists, epidemiologists and medical researchers who want actual exposure data rather than a plain risk number may find the model useful. The application of this model to airports might be most appropriate for first order assessment of risk to occupants in a closed room. It assumes a single "critical dose" above which the risk increases but does not give a specific risk (this can also be viewed as a strength, since it leaves the interpretation of the exposure estimation to the advanced user).

COVID-19 AEROSOL TRANSMISSION ESTIMATOR

Jimenez, J.L., University of Colorado-Boulder.
Web Reference: http://tinyurl.com/covid-estimator

An application of this model is included in: Miller, S.L., Nazaroff, W.W., Jimenez, J.L., Boerstra, A., Buonanno, G., Dancer, S.J., Kurnitski, J., Marr, L.C., Morawska, C. Noakes, C. (2020). Indoor Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale super spreading event. *Indoor Air*, https://doi.org/10.1111/ina.12751

The model in a downloadable spreadsheet calculator based on a box model of dispersion of virus-containing aerosols and CO_2 from exhaled breath for indoor settings. The model predicts the average indoor concentration of viruses and CO_2 for a given indoor activity. The user specifies the size of the space, ventilation and air cleaning, occupancy, number of repetitions of the event, and activity.

The probability of infection is calculated based on the Wells-Riley infection model, from the average virus quanta (infectious doses) present in the air during the activity, and the inhalation rate of the susceptible subjects. Two results are provided: the conditional probability, which assumes that an infected person is present, and the absolute probability, which estimates the probability of an infector being present based on the infection rate in the population.

A useful feature of the model is that the infection rate can be adjusted to account for the fact that many of the people infected with COVID-19 are not very contagious. A number of examples are provided as individual spreadsheets. The model is in the public domain and self-explanatory. It can be copied into a Google Drive Sheet, or downloaded into Excel, where the user can adapt the parameters to their situation. An extensive set of references, tables and frequently asked questions are provided. National Geographic made a 'customized' simpler online version to estimate the risk of airborne COVID-19 in offices, classrooms, and bus rides.
https://www.nationalgeographic.com/science/2020/08/how-to-measure-risk-airborne-coronavirus-your-office-classroom-bus-ride-cvd/

Airport managers might find this model useful to quickly assess the relative risk across their spaces or within specific locations as passenger densities and durations change. The model can evaluate the decrease in infection risk as a function of different control measures, such as increased ventilation with outdoor air, addition of HEPA air cleaning, use of masks, or increasing the quality of the masks, reducing the occupancy, frequency, or duration of the event(s), or using larger indoor spaces.

HARVARD AND UNIVERSITY OF COLORADO BOULDER PORTABLE AIR CLEANER CALCULATOR FOR SCHOOLS

Allen, J., Cedeno-Laurent, J. & Miller, S.
Web Reference: Tool for selecting an appropriate portable air cleaner
https://tinyurl.com/portableaircleanertool
A more comprehensive guide for schools is found: https://schools.forhealth.org/

The calculator provides an easy to use guide for sizing portable air cleaners to increase the clean air delivery rate for a classroom. This model would also be appropriate for airport offices and break rooms needing supplemental ventilation. The calculations are based on a simple-box model that assumes equal mixing in a room. Mechanical systems for classroom ventilation may not meet the minimum 3 ACH. Where opening windows cannot be relied upon to increase air exchange, then portable air cleaners with HEPA-like filtration can provide the necessary supplementary clean air. The model and guide helps facility managers to size air cleaners and provides information about placement and reliable commercial products.

THE SAFEAIRSPACES COVID-19 AEROSOL RELATIVE RISK ESTIMATOR

Corsi, R., Van Den Wymelenberg, K. & Parhizkar, H.
Web Reference: https://safeairspaces.com/

The version 1 (V1.0) model presents relative risk estimates for various indoor configurations and sources strengths, offering insights on how to lower risks based on layered risk reduction strategy. The interface is intended to be easy to understand and educational. The V1.0 model is most useful when seeking to understand the differences in aerosol-based risk profiles between spaces with alternate building air systems, number and types of infected occupants, mask usage, air exchange rates, and filtration rates.

The V1.0 model includes several important assumptions, such as a single, perfectly well-mixed room. In reality, some locations in most rooms will have better or worse airflow and even recirculating “low-flow” zones can occur where virus-laden particles will not be diluted efficiently. It is a single room calculator that assumes air is not recirculated to or from any other rooms. Most spaces passengers use in terminals are large open and connected spaces. Taking the boarding gate areas as an example, the model would treat this as a closed room and could over estimate risk. However, this assumption would be true for other terminal spaces as well, so the relative risk comparisons would still be informative. A useful feature of the model is that it can incorporate recirculation within the same room. This feature accounts for dilution and removal from wall-mounted air conditioning units, portable air cleaners or ceiling mounted VAV and fan coil devices used for localized airflow.

The Safe Air Space model does not calculate risk based on the Wells-Riley quanta method. Rather it calculates the number of infectious particles in the air based on two inputs: the emission rates of infectious particles, and the critical infectious dose to cause a secondary infection. Particle emission rates of coughing, speaking and breathing are derived from the literature, as is the estimation for the critical dose. For ease of comparison among scenarios, the model can select a high emitter and a low emitter. Both types of emitters are presently defined as spending 20% of the time speaking at a moderate volume and having a resting breathing rate. Speaking is assumed to emit 6,000 respiratory particles between 0.5 and 4 microns per minute, as per a high emitter during speaking. Breathing is assumed to emit 600 particles per minute with a size distribution similar to speaking.

The model is more sophisticated than others in that it accounts for particle size. Virus-laden particles of different sizes are estimated to be inhaled and deposited into different regions of the respiratory system (head, trachea-bronchial, and alveolar regions) of all room occupants. Occupants are assumed nose breathers at rates comparable to walking. A dose response function is applied to convert the calculated viral load deposited to estimate likely cases. This V1.0 model would be useful for airport operators to compare risk among locations and quickly assess trade-offs between ventilation and passenger management strategies. The model can be modified to incorporate information related to viral loads as a function of particle size and dose-response curves as they become available.

MIT TOOL MODELS COVID-19 EXPOSURE RISKS IN DIFFERENT SETTINGS

Khan, K., Bazant, M.Z. & Bush, J.W.M. Massachusetts Institute of Technology (MIT)
Web reference: https://www.govtech.com/health/MIT-Tool-Models-COVID-19-Exposure-Risks-in-Different-Settings.html; https://indoor-covid-safety.herokuapp.com/
The science behind the app is also available in a free, self-paced massive, open online course (MOOC) on edX: 10.S95x Physics of COVID-19 Transmission COVID Indoor Safety guideline and an interactive simpler version of the tool can be found at: https://indoor-covid-safety.herokuapp.com/

The model is an easy to use, no cost tool for quickly calculating an estimated amount of time that a person might spend in different types of indoor spaces with different numbers of occupants. It is based on the Wells-Riley infection model that assumes uniform mixing in a single compartment (ventilation zone) with one infectious person present. In the simple version, the source strength can be selected for breathing, speaking or exercise with or without masks. The calculated accumulation of virus (quanta) over time considers only a FF exposure. It permits a reduction in ambient room concentrations either via filtration, using a room air cleaner, or by mechanical filtration. A useful feature of the model is the estimated time to infection, which the user can infer a "safe exposure times" and occupancy levels for indoor spaces.

Available as a downloadable app, a facility manager could set room specifications, ventilation and filtration rates, respiratory activities, and mask compliance to determine the amount of time passengers could safely wait at the boarding gate (without crowding). Airport management could set a risk tolerance level to mitigate indoor COVID-19 transmission in different spaces throughout the airport. For example, airport managers would be able to examine the trade-offs among ventilation strategies and passenger management, where shortening the duration of, for example, security checking and decreasing the number of passengers occupying that space might be more efficacious and less expensive.