RESEARCH REPORT

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Pooled and Shared Travel in the Wake of the Pandemic:

An Inventory and User and Expert Assessments of Vehicle Design Strategies to Mitigate Risk of Disease Transmission

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16. Abstract
This project involved the development of a COVID-19 Risk-mitigating Vehicle Design (CRVD) typology to summarize and analyze the wide variety of vehicle design strategies that have been implemented or suggested to reduce the risk of COVID-19 transmission among workers and passengers in shared and pooled vehicles. Public transit and shared mobility service operators can use the CRVD typology as a reference and guide to aid decision-making in their continued response to the pandemic as well as for future planning. The typology also serves as a launching point for further innovation and research to evaluate the effectiveness of CRVD strategies and their relationship to user preferences and travel behavior, again both within and beyond the current context. This research also explored layperson and expert perceptions of the identified CRVD strategies. By combining these perspectives, a holistic frame can be created to start to develop optimal vehicle design solutions that would be both objectively effective in preventing COVID-19 spread and making travelers feel safe. Ultimately, the hope is that this research can help support a safe return to shared and pooled travel in the wake of the pandemic and contribute to a better—more equitable, sustainable, and enjoyable—mobility future.

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Glossary

Cal/OSHA	California Division of Occupational Safety and Health
CalSTA	State Transportation Agency
CDPH	California Department of Public Health
CRVD	COVID-19 Risk-mitigating Vehicle Design
GSR	graduate student researcher
HEPA [filter]	high efficiency particulate air
HVAC	heating, ventilation, and air conditioning
MERV	minimum efficiency reporting value
OSHA	Occupational Safety and Health Administration
PI	principal investigator
UC Davis	University of California, Davis

Executive Summary

Executive Summary

The COVID-19 pandemic has had dramatic impacts on transportation globally. Widespread shelter-in-place mandates and public health recommendations including social distancing have resulted in reduced travel and travel mode shifts—away from shared and pooled travel modes. For example, California Bay Area Rapid Transit (BART) daily ridership remains low (73-85% below baseline the first week of May 2021).

Shared and pooled travel modes are critical components of a decarbonized and equitable mobility future. They are less energy- and emissions-intensive alternatives to the more dominant mode of single-occupancy vehicles. Vulnerable populations, including millions of essential workers, rely on public transportation and other shared modes and thus have been disproportionately at risk to the degree that these modes leave them susceptible to disease transmission.

For pooled and shared travel to return to and ideally surpass pre-pandemic levels, it is important to implement solutions to reduce the real and perceived risks of infectious disease transmission. Solutions may involve new policies and business models, public awareness programs, and innovative station and vehicle design. This research focuses on vehicle design strategies to facilitate safe and confident use of shared and pooled travel modes in the wake of the pandemic. Pooled and shared travel service operators have been given guidance regarding vehicle design strategies to reduce the risk of COVID-19 spread, but there is a need for a more systematic approach. Most official guidance is industry specific, broadly focused on policies and procedures rather than providing detailed vehicle design considerations and limited to best practices so not including nascent innovations.

The purpose of this research was twofold. First, we set out to understand all the ways in which vehicle design can be modified to mitigate the risk of COVID-19 transmission in pooled and shared travel modes. To this end, we inventoried and analyzed vehicle design strategies that have been implemented or suggested across all major pooled and shared travel modes. We then explored expert and user perspectives regarding the identified vehicle design strategies. To this end, we interviewed pooled and shared mode users and experts from a variety of fields to explore their perceptions of the overall and relative effectiveness of the various design strategies identified.

Identified vehicle design strategies were organized into the COVID-19 Risk-mitigating Vehicle Design (CRVD) Typology consisting of 12 main categories: Seating Configuration, Pathways, Barriers, Ventilation and Air Circulation, Air Filtration and Cleaning, Onboard Surface Sanitization, Hygienic Materials, Hygienic Construction, Touchless Technology, Communication and Monitoring, PPE Provisioning, and Multimodal Support. Strategies were further analyzed to articulate 12 possible mechanisms by which they may help diminish the risk of contracting COVID-19 while riding in shared and pooled vehicles: Physical Distancing, Physical Separation, Reduced Occupant Density, Divergent Orientation, Reduced Exposure Time, Symptom Screening, Surface Hygiene, Avoided Surface Contact, Increased Air Exchange, Strategic Airflow, Air Cleaning, and Separate Air Spaces.

Public transit and shared mobility operators and their regulatory bodies faced are faced the challenge of deciding which of these strategies to adopt. These decisions are further complicated by the need to balance them with other types of strategies (e.g., station design strategies, policies, new business models, website and app features, and new cleaning protocols) to make up a portfolio of complementary solutions to recover ridership and keep workers and riders safe. All this must be accomplished within financial limitations resulting from drastic revenue losses. Paired with public health and industry guidance, the CRVD Typology can help transportation providers assess the range of possible vehicle design solutions and determine which are suitable for their vehicles and services.

The CRVD Typology can also be used by service operators and designers as a guide to generate more solutions, within and beyond vehicle design. For example, they can challenge themselves to identify more strategies of a given type such as Communication & Monitoring strategies (e.g., onboard signs or audio messages explaining ventilation systems). They can also explore categories with few strategies (e.g., Multimodal Support) to see if more can be developed.

Finally, the CRVD Typology outlines a research agenda. Environmental exposure scientists and other experts can study and compare the effectiveness of strategies across and within the CRVD and mitigation mechanism categories and identify gaps in existing relevant literature. Social scientists and travel behavior researchers can assess the influence of CRVD strategies on worker and rider attitudes, intentions, and behaviors. The most effective CRVD strategies are top priority, but it is also important to address user perceptions and prioritize strategies that help workers and riders feel safe.

Our second data collection effort in this research solicited expert (UC Davis faculty and staff in relevant fields) and layperson (student) perspectives on the potential effectiveness of the CRVD strategies to explore common and divergent themes in the ways in which the scientific community versus the general population evaluate the strategies. In-depth, semi-structured interviews revealed an overwhelming consensus among experts and students that CRVD strategies that mitigate aerosol transmission are the most important. Students emphasized Ventilation and Air Circulation the most, while our experts explained that increased Air Exchange is key, which can be accomplished via Ventilation and Air Circulation but also supplemented by Air Filtration and Cleaning. Interviewees expressed that resources should be concentrated on these strategies with the greatest potential for risk-mitigation. Some considered how many of the strategies could be quite expensive endeavors for operators to implement across their fleets, and if such a large investment is going to be made it should “focus on what matters.”

CRVD categories pertaining more to droplet transmission and the mitigation mechanisms of Physical Distancing and Physical Separation were generally ranked relatively high, after those more closely related to aerosol transmission. However, several experts in space conditioning and air quality were very concerned that certain Barriers applications could potentially interfere with airflow, contributing to greater aerosol exposure risk. The implications seem to be that some Seating Configuration and Barriers strategies are probably useful (i.e., both effective and reassuring), but these need to be considered carefully in terms of their implications for airflow.

There were somewhat contradictory views regarding strategies related to fomite transmission and other strategies perceived to be relatively ineffective in terms of preventing COVID-19 transmission and/or perhaps helpful mostly in terms of perceived safety. Many thought such strategies would be worthwhile, particularly if easy to implement, because of other benefits or because “something is better than nothing.” On the other hand, some (particularly experts) feared that ineffective (or insufficient) strategies being implemented (and advertised as COVID-related) might create a “false sense of security” and lead passengers and workers to let their guard down in other ways.

By combining these perspectives, we can create a holistic frame to start to piece together optimal vehicle design solutions that would be both objectively effective in preventing COVID-19 spread and make travelers feel safe. Ultimately, our hope is that this research can help support a safe return to shared and pooled travel in the wake of the pandemic and contribute to a better—more equitable, sustainable, and enjoyable—mobility future.

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Introduction

The COVID-19 pandemic has had dramatic impacts on transportation globally (117th Congress, 2021). Widespread shelter-in-place mandates and public health recommendations including social distancing have resulted in reduced travel and travel mode shifts—away from shared and pooled travel modes. Transportation network companies like Uber and Lyft have halted their pooled ride-hailing options (Lee, 2020). US public transportation ridership decreased by 79% at the beginning of the pandemic and was down 65% from June 2020 through December 2020 (EBP US, Inc., 2021). California Bay Area Rapid Transit (BART) daily ridership remains low (73-85% below baseline the first week of May 2021) (BART, 2021).

Shared and pooled travel modes are critical components of a decarbonized and equitable mobility future (Sperling, 2018). Public transit, carpooling, electric car-sharing, pooled ride-hailing, and micromobility are less energy- and emissions-intensive alternatives to the more dominant mode of single-occupancy vehicles (Hodges, 2010). These modes already made up a relatively small fraction of travel in the US before the pandemic. Now they will likely remain further suppressed in the wake of the pandemic if people continue new mode choice habits (Barbieri et al., 2021; Bratić et al., 2021). On the other hand, those who continue to rely on public transportation—including low-income communities (National Association for State Community Services Programs, 2008), essential workers (TransitCenter, 2020), and communities with higher proportions of African American, Hispanic, Female, and over-45-year-old residents (Liu et al., 2020)—are disproportionately at risk to the degree that these modes leave them susceptible to disease transmission (Liu & Zhang, 2020).

Shared and pooled modes differ in terms of risks of infectious disease, and specifically COVID-19, transmission, depending on a variety of factors. For example, research suggests that ventilation is typically insufficient in buses (Fresno State Transportation Institute, 2020), whereas planes and trains have excellent air change rates (18-30 times per hour) (Bushwick et al., 2020; Boeing, n.d.). Actual risks and public perceptions may differ. For example, a study of perceived risk associated with various travel modes in ten countries found similarly high levels of perceived risk for planes and buses (Barbieri et al., 2021). Strategies like ventilation and air filtration can be complex and unobservable, potentially leading to inaccurate assumptions about risks of shared and pooled modes.

For pooled and shared travel to return to and ideally surpass pre-pandemic levels, it is important to implement solutions to reduce the real and perceived risks of infectious disease transmission (TransitCenter, 2020). Solutions may involve new policies and business models, public awareness programs, and innovative station and vehicle design. This research focuses on vehicle design strategies to facilitate safe and confident use of shared and pooled travel modes in the wake of the pandemic.

This research develops a typology of COVID-19 risk-mitigating vehicle design strategies and explores their objective and subjective value via interviews with experts and users. The results can inform mobility operators to support their adoption of vehicle design strategies as part of a broader portfolio of solutions to protect their workers and riders. Findings also suggest a research agenda for scientists to evaluate and help prioritize among vehicle design strategies. This paper does not make recommendations and does not directly report on relevant research regarding potential effectiveness of the wide variety of strategies discussed. For official recommendations and some literature reviews, see the sources cited in the next section.

Industry Guidance

Pooled and shared travel service operators have been given guidance regarding vehicle design strategies to reduce the risk of COVID-19 spread, but there is a need for a more systematic approach. Most official guidance is industry specific. For example, the Centers for Disease Control (CDC) has provided separate guidance for different types of transit, including bus (2021-b), rail (2021-c), and rideshare/taxis (2021-a). The American Public Transportation Association (APTA) has adapted CDC guidance for public transportation (bus and rail) (APTA, 2020-b). Other examples include the "Runway to Recovery" for mitigating risk in air travel from the US Department of Transportation, US Department of Homeland Security, and US Department of Health and Human Services (2020); guidance for mass transit and marine operators regarding heating, ventilation, and air conditioning from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (no date [n.d.]), recommendations for protecting farm workers in employee vehicles from the Occupational Safety and Health Administration (OSHA) (n.d.). The California Department of Public Health (CDPH), State Transportation Agency (CalSTA), and Cal/OSHA issued industry guidance that was unique in covering both public and private passenger carrier services (2020). Many similar design strategies (e.g., barriers, seating reconfiguration) are recommended across shared and pooled vehicle and service types. Resources tailored to each industry are important, but also analyzing applications across public transit, shared mobility, and air travel could yield a more comprehensive and nuanced shared understanding of vehicle design solutions.

Industry guidance sources do not focus on vehicle design specifically; they are more inclusive, with a strong emphasis on policies and procedures. This holistic approach is essential but makes it difficult to delve into a high level of detail regarding vehicle design strategies. For example, recommendations from the CDPH, CalSTA, and Cal/OSHA include: "Where possible, install Plexiglas or other appropriate barriers in transit and rail vehicles to minimize exposure between operators and passengers" (2020, p.10). This leaves a lot to be determined by the operator, e.g., barrier size, material, location, and whether to install barriers between passengers, all of which vary considerably in practice.

Reports of best practices (Schwartz, 2020; FEMA, 2020) are useful supplements to general industry guidance. For example, in April 2021 the Federal Transit Administration (FTA) released a resource that shares practices that have been implemented by bus and rail operators worldwide during the pandemic, providing links to transit agency websites and news articles where operators can see specific examples of a range of strategies (2021). Though immensely useful, best practices do not include emerging innovative design concepts that have not yet been implemented. APTA notes, "Due to the magnitude of the COVID-19 pandemic, it is likely that transit agencies will want viral outbreak considerations to be included in future vehicle and facility designs and modifications" (2020-a). Broadening the scope to future vehicles creates room for more radical design innovations that should be considered alongside retrofit strategies. These more radical design strategies may help cope with this pandemic and other existing and future infectious diseases.

Methodology

The purpose of this research is twofold. First, we set out to understand all the ways in which vehicle design can be modified to mitigate the risk of COVID-19 transmission in pooled and shared travel modes. To this end, we inventoried and analyzed vehicle design strategies that have been implemented or suggested across all major pooled and shared travel modes. We then explored expert and user perspectives regarding the identified vehicle design strategies. To this end, we interviewed pooled and shared mode users and experts from a variety of fields to explore their perceptions of the overall and relative effectiveness of the various design strategies identified. The following sections detail our data collection and analysis methods.

Inventorying Vehicle Design Strategies

We analyzed vehicle design strategies in iterative stages based on the qualitative content analysis method described in Hesse-Biber and Leavy (2010). We conducted systematic internet searches, gathering information from news articles, public transit websites, industry reports, and academic literature. The literature searches were conducted on Google and Google Scholar using combinations of three types of search terms: (1) shared and pooled vehicle and service types (e.g., “bus”, “subway”), (2) “COVID-19” or “coronavirus”, and (3) terms related to design strategies. The last began with general terms, such as “vehicle design”, and expanded to sets of more specific terms as design strategies were identified (e.g., “seating layout,” “ventilation”). Researchers relied heavily on popular media and industry reports since there is yet limited scholarly research on this new topic.

Searches targeted all major shared and pooled modes: planes, trains, subways, buses, shuttles, ferries, taxis, ridehailing, carpooling, carsharing, and shared micromobility. The focus was on physical aspects of vehicles (i.e., space configuration, onboard features, equipment, and equipment settings/operations), including original equipment and retrofit strategies, and temporary and permanent features either affixed to the vehicle or located on board the vehicle during operation. Design strategies range from innovations still in conceptual stages to pre-existing technologies or settings that were already common or available (e.g., HEPA filters, windows open) but are now being highlighted as protective against the spread of COVID-19 in shared or pooled vehicles. Excluded from the analysis were physical design strategies found at transit stations but not in vehicles, policies (although some vehicle design solutions complement policies), business strategies, transit app and website features, cleaning services (using products or equipment brought onto the vehicle outside of its time of operation), and rider and worker personal equipment they may bring on the vehicle with them that was not supplied by the service operator (including masks, gloves, no touch tools to open doors, and smart helmets that detect the temperatures of people nearby).

Vehicle design strategies were recorded with descriptions, images, and references to the media and/or academic articles that discuss them. Each strategy was also coded with the applicable vehicle/service type(s) mentioned in the sources (only those mentioned in sources and not theoretical considerations about potential applicability), and whether it had been implemented yet according to our sources (as opposed to a conceptual design or under development). Data collected on each strategy are available in the online supplementary material, which also provides links to sources for each identified strategy is available here: https://airtable.com/shr5z4uh9zMZ1aqoZ.

Vehicle design strategies were organized into a COVID-19 Risk-mitigating Vehicle Design (CRVD) Typology. We attempted to create exhaustive and mutually exclusive categories based on considerations of structural (e.g., physical form and location in the vehicle) and functional characteristics (e.g., outcomes or services provided). A design student created graphics to illustrate most identified strategies (some graphics convey multiple specific, related strategies). The classification scheme and illustrations serve to summarize and distill the variety and complexity of observed vehicle design strategies into main ideas and themes that can be more easily communicated to policymakers, transit service operators, and vehicle manufacturers.

Interviewing Users and Experts

After we inventoried the design strategies, we conducted two series of in-depth, semi-structured interviews. The aim was to gauge public perceptions of effectiveness and understand potential actual effectiveness from experts. All interviewees were affiliated in some capacity with University of California, Davis (UC Davis).

To begin to gauge user perspectives on perceived effectiveness and preferences for the various vehicle design strategies, we interviewed 20 UC Davis students, all regular users of some type of public transit or shared mobility prior to the pandemic. These interviews with a convenience sample are intended as initial explorations to identify key themes, and we hope to later conduct a large-scale survey with a representative sample of essential workers, including transit and shared mobility workers.

Student interviews were conducted by the principal investigator (PI) and four research assistants. They were typically one-hour long and conducted online over video calls (using Google Meets). An interview protocol was developed and programmed in Qualtrics survey software. Interviewers recorded notes in the Qualtrics instrument while they conducted the interviews. The CRVD illustrations were organized into a Google Slides presentation to screenshare with participants during the interviews.

Interviewers presented illustrations of each CRVD category, one at a time in random order, to every participant. After briefly describing each strategy, avoiding explanations of how they are intended to combat COVID-19 spread, interviewers provided a series of prompts, including three main prompts and several follow-up prompts that were provided as needed to elicit responses:

- Do you think these strategies can lower the risk of COVID transmission in public and shared transportation?
    - How so?
    - Do any of these seem like they would be more effective?
    - Do any of these seem like they would be less effective?
- Unrelated to COVID, is there anything else you like or dislike about these strategies?
    - Would you want to see them even after COVID is no longer a major concern?

- Do you think [CRVD category] is more or less important for different types of vehicles?
    - How so?

At the end of the interview participants were shown a list of all the CRVD categories and asked to rank them from the most important to the least. Interviewers offered to revisit illustrations if interviewees had trouble remembering the categories (they did not).

To gauge expert opinions on the potential for the CRVD strategies to mitigate risk, we interviewed 23 UC Davis faculty, research, and administrative staff, including 5 physicians and 3 administrative staff at UC Davis Department of Internal Medicine Division of Infectious Diseases and Infection Prevention; 1 respiratory toxicologist; 3 engineers whose foci include airborne pathogen exposures, 6 engineers who specialize in Heating, Ventilation, and Air Conditioning and/or related controls systems; 3 epidemiologists with expertise in air pollutant exposures (2) and environmental justice; and 2 social scientists with public health and communications backgrounds, both conducting research on public perceptions and response to COVID-19. Interviewees included persons in senior leadership roles at relevant offices and divisions within UC Davis Health and several Organized Research Units (ORUs, i.e., research centers).

The PI and a Graduate Student Researcher (GSR) conducted interviews with experts. They proceeded similarly to the student interviews, with some exceptions. Namely, we did not cover all CRVD categories with all experts. For example, we focused on the categories related to airborne transmission when we spoke with air quality and space conditioning experts. For all others, we typically covered all categories unless we needed to shorten the interview to less than an hour. We also asked for expert perspectives on the mitigation mechanisms, which were added to the slide deck with names, descriptions, and icons. We did not have them rank all mechanisms, but rather asked them to talk through them and give a sense of how they would prioritize them, e.g., top three, or most and least important. In short interviews, we led with the mechanisms slide and question and then selected CRVD categories related to interviewees' top priorities to discuss with them for the remainder of the interview.

Qualitative analysis of interviews combined insights from experts and students to understand the degree to which design solutions may both objectively mitigate the risk of COVID-19 transmission and be acceptable and perceived as valuable to consumers of shared and pooled transportation. We used grounded theory to identify emergent patterns in the data.

COVID-19 Risk-mitigating Vehicle Design (CRVD) Typology

Identified strategies were organized into the CRVD Typology consisting of 12 main categories (Table 1). The Appendix provides a series of graphics to illustrate each category of CRVD strategies.

Table 1. CRVD Typology Main Categories and Definitions

Vehicle Design Strategy Type	Definition
Seating Configuration	Seating layout and other features that specify where riders sit or stand during transit, including location and orientation
Pathways	Features that specify how riders move about the cabin, e.g., boarding and deboarding
Barriers	Partitions of various sizes, configurations, and materials between passengers or passengers and workers
Ventilation and Air Circulation	Equipment or setting that improves ventilation (brings outside air into the vehicle, moves inside air out) or air circulation (movement of air within the cabin)
Air Filtration and Cleaning	Equipment that cleans the indoor air that is being recycled or introduced from outdoors, by trapping and/or killing airborne particles
Onboard Surface Sanitization	Equipment and settings that implement surface cleaning processes
Hygienic Materials	Materials that contribute to vehicle hygiene
Hygienic Construction	Construction techniques that contribute to vehicle hygiene
Touchless Technology	Adaptations or new mechanisms, including automated technologies, that limit driver/rider physical contact and interaction with the vehicle
PPE Provisioning	Onboard PPE dispensers
Communication and Monitoring	Features that collect and/or display information to passengers and/or service providers
Multimodal Support	Features that facilitate multimodal trips to limit time in more shared/pooled modes

Strategies were further analyzed to articulate 12 possible mechanisms by which they may help diminish the risk of COVID-19 transmission on shared and pooled vehicles (e.g., increasing distance between passengers; Figure 1). The following sections give an overview of each category, including examples and hypotheses regarding the mechanisms by which they may reduce risk. Again, this is an inventory of design concepts and not a set of recommendations.

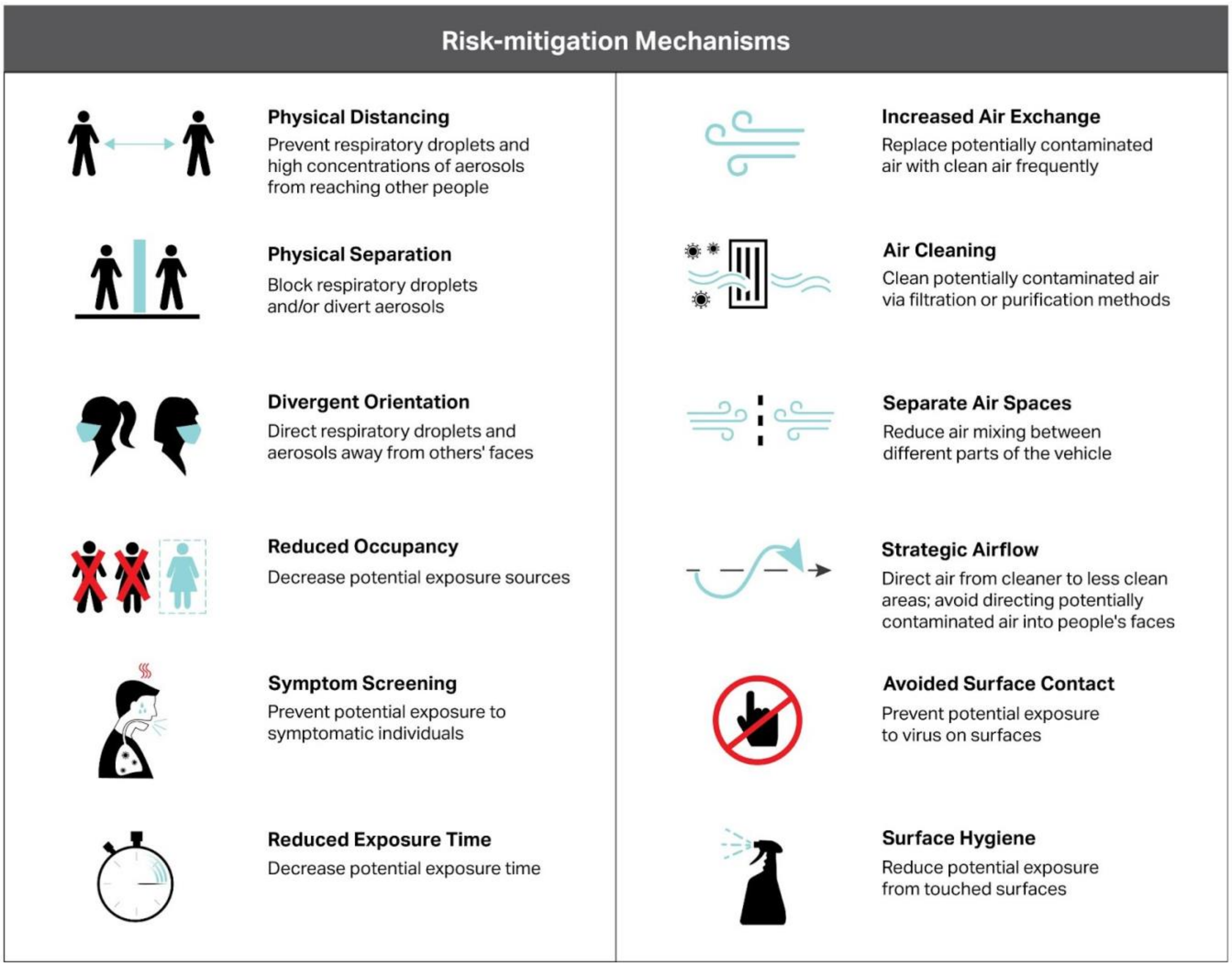

Figure 1. Risk-mitigation Mechanisms

Seating Configuration

Seating configuration includes three general strategies: eliminating seats, spreading them out, or changing their orientation. Eliminating seats can increase distance between passengers and reduces overall vehicle occupancy. Seats and standing passenger spots may be designated as approved or off-limits using signs or stickers, without any real structural changes. Seats may be temporarily removed or repurposed through flexible structural changes (e.g., removable seats). There are also proposals for permanent new layouts that include a reduced number of seats.

Unlike eliminating seats, spreading out or changing orientation do not necessarily require reducing occupancy. Three methods of spreading out seats (or passengers) were identified: designating a seating area (e.g., train car) for vulnerable populations to keep them away from others; spreading seats out into spaces not typically used for seating; and staggering/off-setting seats within rows. These all involve increased physical distancing. Re-orienting seats, including flipping middle seats and removing tables in train cars to flip alternating rows so all face the same direction, might increase distance slightly, create some degree of physical separation (more so if used in conjunction with a Barriers strategy), or perhaps to redirect passengers' respiratory particle trajectories away from each other's faces (mechanism: Divergent Orientation). A seating reorientation strategy with a different aim is to use longitudinal bench seating instead of transverse arrangements for easier cleaning (mechanism: Surface Hygiene).

Pathways

In addition to specifying or changing where passengers sit (or stand) during the ride, vehicle design strategies can specify or change how passengers move about the cabin, e.g., while (de)boarding. These strategies also leverage distancing and/or orientation. Some bus services are roping off the front of the bus and requiring passengers to use the rear door only, limiting their proximity to the driver. On the other hand, some vehicles are designating separate doors for entry versus exit. Other Pathways strategies include an open gangway layout (i.e., where the connections between cars do not have doors [see Pathways illustration in the Appendix]) so passengers can more easily move from one train car to another (perhaps less crowded), and relocating ticketing machines in buses, where passengers linger before finding a seat, further away from the driver.

Ventilation and Air Circulation

This category consists of equipment or system settings that improve ventilation (exchange with outdoor air) and circulation (movement of air within a space). Strategies to improve ventilation include opening windows, doors, and roof hatches, even when heating or air conditioning; running the fan continuously and at maximum speed, using fresh (outdoor) rather than recycled air heating, ventilation and air conditioning (HVAC) settings; and adding/using vents and fans, including exhaust fans. There are also recommendations to control airflow within the vehicle strategically, including directional airflow from clean to less clean areas, configuring open windows to create cross-ventilation flow, and indirect airflow from floor vents upward instead of horizontal flows directly into riders' faces.

Air Filtration and Cleaning

In terms of air filtration, advanced mechanical filters are widely recommended, including High Efficiency Particulate Air (HEPA) filters and filters with a high Minimum Efficiency Reporting Value (MERV) rating (e.g., MERV 13). These can be installed in the HVAC system or used in an after-market device added to the vehicle (e.g., a cupholder-sized air purifier with a HEPA filter). Other air cleaning technologies include ultraviolet (UV) light (specifically UVC) and ionization, which can be integrated into the HVAC system or provided by an after-market device. UVC is extremely damaging to human eyes and skin, so when used outside of the HVAC ducting it needs to be enclosed in a system located on the ceiling that treats the air at the top of the vehicle without exposing riders.

Onboard Surface Sanitization

Onboard Surface Sanitization involves equipment installed in the vehicle that controls cleaning processes, as opposed to cleaning services conducted manually or with equipment brought onto the vehicle during servicing. Four onboard cleaning methods were identified: light, heat, chemical, and air. UVC and LED lamps have been installed in vehicles, intended to kill the virus on surfaces between transit services. Foggers have been installed to spray chemical disinfectants between uses. Adapting an HVAC system to heat the vehicle cabin to a very high temperature is another strategy intended to kill the virus on vehicle surfaces between uses. Positive air pressurization of a bus cabin has been tested as a strategy to prevent the virus from settling on surfaces during vehicle operation.

Hygienic Materials

Recommendations can be found for easy-to-clean surface materials, including to avoid or remove cloth (e.g., rugs and fabrics on seats) and other porous materials, and/or use protective coatings, including clear-coat floor finishes, to facilitate cleaning. Relatedly, durable materials to hold up to harsh and frequent cleaning have been recommended, as well as disposable seat and floor coverings. Biocidal materials (e.g., copper) and coverings (films and spray-on shields), i.e., those with internal properties that might irradicate the virus, have also been suggested. One source suggested replacing plastic surfaces with cardboard.

Hygienic Construction

Two general categories of construction techniques have been considered. The first is minimizing seams and joints, including non-ribbed flooring, sealing floor seams, and upholstering seats so that the bottom and back connection is seamless to avoid a gap where dirt and germs can accumulate. The second is accommodating cleaning, including detachable food trays, cantilever seating (easier to clean under), planning space for cleaning equipment to come on board, floor-mounted piping to hook up a hose to clean, and holes in the bottom of seats (also for wet cleaning).

Touchless Technology

Touchless Technology strategies are divided into three sub-categories: automation strategies that eliminate the need for physical contact with the vehicle and/or reduce vehicle occupancy; low-touch mechanical strategies that minimize physical contact; and personal props that involve replacing shared surfaces with accommodations for personal items. Examples of automation include fully automated (i.e., driverless) vehicles, touchless card and ticket scanners, automated doors, and automatic (rather than pumped) hand sanitizer dispensers. Examples of low-touch mechanisms include a pedal door opener and pedal tray table control. Personal props include personal handholds distributed to passengers to attach to vehicle grab rails to avoid the shared surface, and mounts in planes for personal mobile electronic devices and bags, replacing shared touchscreen tablets and seat-back literature pockets, respectively.

Personal Protective Equipment (PPE) Provisioning

Service operators have added dispensers to their vehicles to supply users with hand sanitizer, disinfecting wipes, and masks. In addition to onboard dispensers, many operators are supplying PPE to their workers. Other related strategies include locating trash receptacles in vehicles (e.g., to dispense of wipes), and making sure onboard restrooms are adequately stocked with soap and dryers or paper towels. These strategies are indirectly related to the risk-mitigation mechanisms listed in Table 2, since the mediating role of occupant behavior is more significant, but they have implications for Surface Hygiene, and Physical Separation in the case of masks.

Communication and Monitoring

Communication & Monitoring strategies are divided into three sub-categories: Education and Prompts, Environmental Feedback, and Symptom Detection and Contact-tracing. Education and prompts remind passengers to comply with the federal mask mandate and other operator policies and recommendations (e.g., to practice good hygiene), as well as communicate CDC guidance and general COVID-19 information. Environmental feedback involves devices that monitor and/or display dynamic information about environmental conditions in the vehicle related to the risk of virus transmission, such as occupant density, surface cleanliness, and CO_2 levels. Symptom detection and contact-tracing strategies collect data to monitor passengers. Examples include a QR code in pooled vehicles that passengers scan to enable contact-tracing in the case of exposure to another passenger with COVID-19, and cameras with facial recognition to detect mask-wearing or thermal imaging to detect whether a passenger has a fever.

Multimodal Support

A unique feature of a train car design concept was the flexible repurposing of some seating as convenient bike storage for passengers. This Multimodal Support strategy could facilitate or encourage the use of bikes in conjunction with pooled and shared travel modes in order to shorten the duration of trip legs made in pooled vehicles where exposure risk is higher. Although no mentions of added bike racks for this purpose were found for other types of shared and pooled vehicles, this strategy is also relevant for cars (taxi, ridehailing, and vanpooling) and buses.

Expert and User Perspectives

High-level emergent themes from the interviews correspond to the modes of COVID-19 transmission: fomite transmission (through touching contaminated surfaces) and droplet/aerosol transmission (respiratory particles landing in mucous membranes of the eyes, nose or mouth, or being inhaled). Interviewees' opinions of CRVD strategies correlated with whether the strategy primarily, and directly, addresses one or the other of these transmission modes. These categories are thus used to organize the analysis below. Several types of CRVD strategies are indirectly related to one or both of these transmission modes; they rely on user behavior to be effective. Interviewees' opinions on these will be discussed last.

Fomite Transmission

Four CRVD categories are primarily related to fomite transmission: Onboard Surface Sanitization, Hygienic Materials and Construction, and Touchless Technology (Table 1). Expert and student interviewees felt that these strategies would have limited value to mitigate the risk of COVID-19 transmission because fomites are not the main mode of spread. One expert referred to COVID-19 fomite transmission as a "red herring…It isn't that it helps 0%, but why waste resources?" Another similarly observed, "It's not a no-yield, but not a priority. I wouldn't direct my resources [to these strategies] but would not ignore [them] if easy to implement." When asked to rank the risk-mitigation mechanisms, virtually all experts placed those related to fomite transmission (Avoided Surface Contact and Surface Hygiene) at the bottom of their list.

Although interviewees felt these strategies should not be high priority in terms of resource allocation for short-term solutions to the current pandemic, the idea of enhanced cleanliness was universally appreciated. Some medical experts pointed out that other diseases (including perhaps the next pandemic) do spread easily through fomites, one noting that "shared surfaces are always going to be an issue." Interviewees felt that these strategies would be relatively more important for high-turnover vehicles where there is little opportunity for cleaning in between services.

A common theme relating to user perceptions of these strategies was the importance of visibility and/or education, e.g., "People see UV robots in the hospital, and you explain what it's doing, they immediately feel a lot safer." Social science experts suggested including an educational component to communicate how unseen and/or unfamiliar strategies work. When people know about these strategies it might give them "peace of mind"/make them "feel safer" even though fomite transmission is not a major concern. An expert considered how this might do more harm than good, "Do you actually end up hurting people because they pay more attention to those? [They think,] 'I'm doing that, I'm fine.'"

Touchless Technology

Experts and students both found automation strategies in the Touchless Technology category appealing and useful beyond the context of COVID-19. They generally had fewer positive feelings about the low-touch strategies, remarking that foot pedals may not be accessible to everyone or may get in the way and hooks and stands for personal devices would still be shared surfaces. However, one expert was passionate in her disgust for seat-back pockets in airplanes, so their removal was happily met.

Hygienic Materials and Construction

Students approved of the idea of durable materials to hold up to frequent and/or harsh cleaning and medical experts confirmed their value based on experiences with hospital equipment, although members of each group mentioned possible sacrifices to comfort during long trips on hard seats. Students were intrigued by biocidal materials but skeptical due to the unobservable nature of the processes, whereas experts were familiar with the technologies and somewhat less impressed; they validated their potential but also raised concerns such as lack of evidence of effectiveness outside lab contexts, copper being difficult to clean, and surface contamination interfering with light-activated self-cleaning materials. Cardboard was popular with no one. Some disliked the waste associated with disposable seat and floor coverings.

Onboard Surface Sanitization

Students were largely unfamiliar with Onboard Surface Sanitization strategies, with UV being an exception for some, and most had negative reactions to the idea of chemical foggers (we did not specify what types of chemical are used). Specifically, they feared for passenger exposure to harmful chemicals and smells. Experts were generally more familiar with these strategies, with the exception of positive pressure, and less surprised by the use of chemical foggers. One expert (physician) noted that routine cleaning has been shown effective against even the more virulent strains of COVID-19. Another expert (epidemiologist) considered that the use of heavy chemical cleaning may be warranted under conditions of high community spread of a virus with significant fomite transmission but should be discontinued after the threat subsides. Concerns were also raised about potential harm to vehicle surfaces (from UV, heat, and chemicals).

Droplet and Aerosol Transmission

Five CRVD categories are primarily related to droplet and aerosol transmission: Seating Configuration, Pathways, Barriers, Ventilation and Air Circulation, and Air Filtration and Cleaning (Table 1). These strategies might reduce the likelihood of larger, heavier respiratory droplets from one rider landing on another rider's mouth, nose, or eyes, and/or reduce the likelihood of riders inhaling particles. Experts explained that these transmission modes are difficult to tease apart but some suggested that "inhalation is the greatest concern."

The students we interviewed had knowledge of the latest information about the relatively greater risk of droplet/aerosol transmission. When we asked them to rank the CRVD categories, Space Conditioning strategies were ranked the highest, on average, followed by Barriers. (Space Conditioning was an umbrella category used in the interviews, encompassing Ventilation and Air Circulation and Air Filtration and Cleaning [Table 1].) It is important to note that this may not be representative of the general population or groups that rely more on pooled or shared modes.

Experts overwhelmingly ranked Increased Air Exchange as the top priority mitigation mechanism, with some grouping it with closely related mechanisms, Air Cleaning and Strategic Airflow. One summarized, "Dilution is always the solution to pollution." Others warned, "If you don't have high airflow, you're missing the boat" and, "If you don't have sufficient ventilation overall there could be a large background [of respiratory particles] building up for indirect exposure." They noted that Separate Air Spaces would be highly effective but there are limited applications for that in pooled travel, exceptions including operator compartments that are sealed off from the rest of the cabin and full barriers between the front and back seat in taxis and ride-hailing vehicles, which would have to be used in conjunction with space conditioning strategies that do not cut anyone off from fresh air ventilation and heating and cooling.

Ventilation and Air Circulation

Ventilation strategies were popular among students and experts. The general sentiment was the more fresh/outdoor air the better (e.g., open air shuttle being the epitome of good ventilation), with some caveats. Members of both groups mentioned that maximizing ventilation could make the ride less comfortable or interfere with aerodynamics depending on vehicle speed and weather and/or increase energy consumption if also heating and cooling. Bringing in outdoor pollution, e.g., from the roads or underground subway systems, was also a concern; some experts advised that incoming outdoor air should be filtered. One ventilation strategy that was met with some skepticism was an air vent built into each head rest air (see Ventilation & Air Circulation illustration in the Appendix). Some students seemed to think it was gimmicky. Two experts wondered whether the bus ventilation strategy that directed air from the front to the rear, up and out the roof, might leave the passenger seating area stagnant.

We learned that airflow is extremely complex. It took a number of interviews with experts to reach an understanding of some issues. At first, we were hearing seemingly contradictory statements. For example, one HVAC engineer noted that it is important to have airflow at people's heads, and they liked how planes have the vents streaming right at passengers' faces. Others thought the indirect airflow strategy (vertical airflow in front of passengers rather than horizontal airflow at head level) made sense. The unifying ideas seem to include plug flow (a type of laminar airflow with little to no turbulence to avoid mixing contaminated and fresh air) moving in one direction from clean (occupied) to less clean (unoccupied) areas where exhaust outlets are located, such that particles expelled from a potentially infected person will not be entrained in a flow that goes into someone else's face and will be quickly moved out of the vehicle.

Other airflow complexities somewhat unsolved from the combined interviews include debates about the direction of vertical airflows. Some experts suggested that upward movement, as in the indirect airflow strategy or displacement ventilation, would complement the natural rising of our breath that is warmer than the indoor air and could be effectively combined with exhaust at the top of the vehicle. On the other hand, one expert thought it might make more sense for road vehicles to draw cleaner air from above rather than below the vehicle and another said, "Airflow in vehicles is much more driven by the HVAC than buoyancy (hot air rising). If hot air rising is a factor, then your air exchange is too low." Experts explained that there are many factors affecting airflow, so controlling it is very difficult, and studies would need to be done for each specific vehicle in a variety of contexts, and even then, it would be hard to predict reliably.

Air Filtration and Cleaning

Experts explained that air filtration and cleaning strategies (specifically mechanical filtration and UV germicidal irradiation in HVAC system ducting or upper-room systems) can function similarly to enhanced ventilation in terms of increasing air exchange. Some experts recommended that only code-required ventilation be ensured and then supplemented with enhanced air cleaning to attain a protective air change rate. Students were largely unfamiliar with but generally liked the idea of filtration and cleaning strategies, although they also wanted to be assured of enhanced ventilation. One explained that they would be more assured by ventilation strategies compared to air cleaning because “you can feel that they're working.”

Experts familiar with ionization disapproved of it, referring to research showing a lack of effectiveness and concerns about generating other air pollutants (i.e., ozone, albeit some thought perhaps in negligible amounts); one worried that incorporating these technologies might contribute to a false sense of security. HVAC experts also noted that incorporating any new cleaning technology into the HVAC system introduces more maintenance requirements and room for error. Introducing after-market/portable air purifiers seemed a good idea to most experts, with caveats including that they are intended for use in closed spaces, need to be sized appropriately for that space, and products range in quality: “It’s important to be cautious of buying purifiers off Amazon. You want one with an industrial or FDA claim (medical grade).”

Barriers

Many experts and some students mentioned the distinction between droplets and aerosols when considering the potential effectiveness of barriers, noting that they can be useful to protect from the former but not so much the latter. Some experts described how barriers are more useful if people are going to be interacting/talking. This is ironic considering interviewee reports of barriers being difficult to communicate through and people tending to peek around them to talk. Still, experts and students agreed barriers to block workers from the many passengers talking at them, and potentially from other assaults as well, were a good idea. Students and experts also agreed that hard barriers would be preferable to soft for ease of cleaning (also noting that they would indeed need to be cleaned) and reliability (easier to keep in place).

Experts saw barriers as less important if masks are worn (properly) since masks serve a similar function but more effectively since they are closer to the potential exposure site. However, many also suggested that barriers might have a “psychological impact”, making passengers feel safer. In fact, students confirmed this hypothesis, perceiving barriers as “second-degree protection” beyond mask-wearing.

Even while acknowledging shortcomings of barriers for aerosol transmission, students figured they “can only help” and the general sentiment was the bigger the barrier the better. Some experts disagreed with the idea that barriers “can only help,” noting that some barriers may actually do harm by creating stagnant air pockets that could increase aerosol transmission. In this case, the bigger the barrier the more it may disrupt airflow; barriers perpendicular to airflow or extending over passengers’ heads (as in pod seating) might be especially likely to create pockets of stagnant air.

Seating Configuration

Generally, interviewees felt that Eliminating Seats, which reduces vehicle occupant density (i.e., the number of passengers), would be more effective than strategies that only increase physical distancing (Spreading Out) or those that reorient the direction passengers face (Reorienting). Students were relatively more appreciative of Spreading Out strategies than experts (particularly air quality and space conditioning experts), which may reflect differences in understandings about aerosol and droplet transmission. Many noted that people usually spread out anyway, preferring to sit away from others not in their party.

Experts discussed the importance of reduced occupant density in relation to aerosol exposure risk, noting that ventilation requirements are based on occupant density. One summarized, “You can’t ventilate your way out of crowding.” Another explained, “It comes down to occupancy density… The more people you have, the density of aerosols increase… Imagine every person has a bottle of perfume with a cap off… When you walk in the bus, you’re going to be like, ‘Whoa!’ It doesn’t matter how far apart people are.”

Some experts also considered how seating arrangements might interact with airflow. For example, one considered, “Someone is always going to be in a bad seat.” This related to two ideas: one is that airflows might move across passengers (e.g., from the front to the back of the vehicle) before exhausting, so the person in the last seat in line gets the most exposure, and the other is the idea that aisle seats have greater exposure to people walking up and down the aisle.

As far as preferences among the Eliminating Seats strategies, most thought that temporary or flexible solutions were more practical than permanent designs with fewer seats. Even though most liked the idea of less crowding in vehicles beyond the context of COVID-19, some had doubts about corporations or transit operators being willing or able to sacrifice higher ridership and did not want to incur higher costs to ride as a result of decreased occupant density. A few discussed the negative environmental impact of permanently increasing the number of vehicles to provide the same level of service. Among the temporary or flexible solutions for eliminating seats, many (particularly students) thought temporarily removing or repurposing seats would be better than relying on signage and ropes designating seats as off-limits that passengers might ignore.

Of all the CRVD categories, personal preferences seemed to play the biggest role in interviewee reactions. Some liked the idea of single seats, while others pointed out that groups could not sit together (this was a concern with a few configurations, with some suggesting seating options for different size parties). A few liked the flipped middle seat idea, but many had concerns, including that it might increase risk since people would be facing each other more and perhaps it would encourage talking, or it might be socially awkward, and it could cause motion sickness. Similarly, some liked the idea of double-decker seating in planes, while others did not.

Passenger-mediated Strategies

Three CRVD categories were less strictly tied to either fomite transmission or droplet/aerosol transmission: PPE Provisioning, Communication and Monitoring, and Multimodal Support. What these three have in common is a greater degree of dependency on rider behavior. Their effect on either fomite or droplet/aerosol transmission risk is indirect, mediated by actions taken by passengers (e.g., using provided PPE, following posted guidance, or bringing their bike on the train and getting off a couple stops early). Riders can influence other strategies (e.g., rolling down a window for ventilation or sitting in a seat marked as off-limits), but these three categories are more exclusively under the riders' control.

PPE Provisioning

All interviewees thought PPE Provisioning was a good idea, although one expert pointed out that these strategies are not considered PPE in the medical community (e.g., their definition would include things like N-95 masks after a medical fit test). On average, students ranked this category as the third most important CRVD category after Space Conditioning and Barriers. (Space Conditioning, a category used in student interviews, consisted of Ventilation and Air Circulation as well as Air Filtration and Cleaning.) The importance of masks was universally acknowledged by our sample, which again we note is not necessarily representative of most pooled and shared mobility users.

Interviewees, including those in the medical field reporting on experiences with many patients, described how hand sanitizer use has become routinized for many people and public dispensers are widely used, to the point where some people have developed preferences (and distastes) for certain types of sanitizers. One expert noted that hand sanitizers can give off volatile organic compounds (VOCs), so being in a vehicle where many people walk in and use sanitizer could be harmful, particularly for vulnerable groups (e.g., asthmatics). There was some concern about disinfecting wipes generating waste (disposable masks as well). One expert observed that these strategies are not only helpful in preventing the small risk of surface transmission, but also help to create a "prevention and safety culture." Another suggested that pairing these strategies with "ads or announcement over the PA systems" could be effective in encouraging desired behaviors, which relates to the category we discuss next.

Communication and Monitoring

Most interviewees thought prompts to abide by policies and recommended practices were useful reminders, though not high-impact strategies. Some said that most people will be following the rules anyway, at least in terms of observable practices. One expert explained that these strategies are important when guidance is inconsistent across settings and changing. Quite a few people also pointed to the utility of these strategies as an aid to help employees enforce the rules (giving them something to point to when they have to ask someone to comply), and to help passengers apply social pressure to someone not conforming (e.g., "saying [prompts] out loud is a good way to glare at your neighbors").

Regarding messaging formats, some mentioned that basic signage can be overlooked, and audio announcements can be more salient but sometimes annoying. Other considerations mentioned were language, literacy level, and clarity of images. Experts stressed the need to use multiple languages and clear graphics to overcome language and literacy barriers.

Although less clearly tied to risk-mitigation and therefore not included in our typology, mobility services providers can use these same communication methods to convey educational messages. This was something both students and experts recommended in various contexts. For example, related to the theme that people will be more reassured by strategies they can see or understand, interviewees recommended that operators provide information about invisible or unfamiliar strategies, such as hygienic materials and air filtration. Social scientist-interviewees explained the importance of including an educational component to promote awareness and understanding, and thus perceived safety. One noted that varying levels of literacy regarding relevant topics is particularly challenging when trying to explain complicated technologies (e.g., HVAC) and scientific evidence (e.g., when providing general information about disease transmission).

Symptom and mask compliance detection and contact tracing strategies were largely met with skepticism regarding performance/effectiveness and enforcement. Medical experts had experiences with thermal imaging and related technologies and were unimpressed with their accuracy and validity. Students also mentioned insufficiency to identify asymptomatic carriers. Several students mentioned biases in facial recognition cameras. Students and experts suggested these occupant-monitoring strategies would be highly unpopular among many Americans due to perceptions of privacy infringement; several students had these concerns themselves. Some pointed out that certain (and more vulnerable) populations (e.g., older adults) would not be adept at using QR codes. The strongest theme regarding these strategies was doubts about feasibility and efficiency of enforcing these features. For example, interviewees expressed reservations about how the strategies would slow the boarding process, and they questioned whether and how symptomatic and non-complying riders would be handled.

Unlike strategies where the mobility service personnel monitor passengers, environmental feedback strategies enabling passengers to monitor the service environment were generally well-received. Instead of restricting rider freedoms, environmental feedback strategies were perceived as giving them more freedom, e.g., “it gives passengers information to make their own choices”, “good for the individual so they can make their own decisions and assessments.” Occupancy feedback and color-changing seats to convey cleanliness were particularly popular, CO_2 feedback less so. Students talked less about this strategy, possibly indicating unfamiliarity with the idea, and sometimes made it clear they misunderstood it; relatedly, experts discussed the need to provide ample education with these strategies, particularly CO_2 feedback. Another important factor is whether passengers can respond to the information, e.g., move to a less crowded train car or find a cleaner seat. There might be few applications where passengers can increase vehicle ventilation when CO_2 levels are high (and the feedback interface would need to communicate those opportunities). In the absence of control, interviewees said environmental feedback “is going to make people more panicked.”

Multimodal Support

Most people thought the one specific strategy in this category (bike racks—adding them and/or improving accessibility) was desirable and could help reduce risk if people reduced the amount of time spent in the pooled vehicle, with experts referencing the CDC guidance regarding time limits for reducing indoor exposure risk (i.e., 15 minutes). However, many had doubts about how much it would encourage riders to shorten their trips. Most thought it was a good idea beyond the context of the current pandemic, to facilitate biking.

Discussion

Typology

This research distilled into the CRVD Typology the wide variety of vehicle design solutions aimed at mitigating the risk of COVID-19 transmission in public transportation and shared mobility. Public transit and shared mobility operators and their regulatory bodies face the challenge of deciding which of these strategies to adopt. These decisions are further complicated by the need to balance these with other types of strategies (e.g., station design strategies, policies, new business models, website and app features, and new cleaning protocols) to make up a portfolio of complementary solutions to recover ridership and keep workers and riders safe. All this must be accomplished with financial limitations resulting from drastic revenue losses. Paired with public health and industry guidance, the CRVD Typology can help transportation providers assess the range of possible vehicle design solutions and determine which are suitable for their vehicles and services.

The CRVD Typology can also be used by service operators and designers as a guide to generate more solutions, within and beyond vehicle design. For example, operators and designers might develop more strategies of a given type, such as Communication & Monitoring strategies (e.g., onboard signs or audio messages explaining ventilation systems). They can also explore categories with few strategies (e.g., Multimodal Support) to see if more can be developed.

Finally, the CRVD Typology outlines a research agenda. Environmental exposure scientists and other experts can study and compare the effectiveness of strategies across and within the CRVD and mitigation mechanism categories and identify gaps in existing relevant literature. Social scientists and travel behavior researchers can assess the influence of CRVD strategies on worker and rider attitudes, intentions, and behaviors. The most effective CRVD strategies are top priority, but it is also important to address user perceptions and prioritize strategies that help workers and riders feel safe.

Interviews

Our second data collection effort in this research solicited expert (UC Davis faculty and staff in relevant fields) and layperson (student) perspectives on the potential effectiveness of the CRVD strategies to explore common and divergent themes in the ways in which the scientific community versus the general population evaluate the strategies. In-depth, semi-structured interviews revealed an overwhelming consensus among experts and students that CRVD strategies that mitigate aerosol transmission are the most important. Students emphasized Ventilation and Air Circulation the most, while our experts explained that increased Air Exchange is key, which can be accomplished via Ventilation and Air Circulation but also supplemented by Air Filtration and Cleaning. Interviewees expressed that resources should be concentrated on these strategies with the greatest potential for risk-mitigation. Some considered how many of the strategies could be quite expensive endeavors for operators to implement across their fleets, and if such a large investment is going to be made it should “focus on what matters.”

CRVD categories pertaining more to droplet transmission and the mitigation mechanisms of Physical Distancing and Physical Separation were generally ranked relatively high, after those more closely related to aerosol transmission. However, several experts in space conditioning and air quality were very concerned that certain Barrier applications could potentially interfere with airflow, contributing to greater aerosol exposure risk. A few pointed out that Barriers could also increase the risk of fomite transmission if not cleaned often. The implications seem to be that some Seating Configuration and Barriers strategies are probably useful (i.e., both effective and reassuring), but these need to be considered carefully in terms of their implications for airflow.

There were somewhat contradictory views regarding strategies related to fomite transmission and other strategies perceived to be relatively ineffective in terms of preventing COVID-19 transmission and/or perhaps helpful mostly in terms of perceived safety. Many thought such strategies would be worthwhile, particularly if easy to implement, because of other benefits or because “something is better than nothing.” On the other hand, some (particularly experts) feared that ineffective (or insufficient) strategies being implemented (and advertised as COVID-related) might create a “false sense of security” and lead passengers and workers to let their guard down in other ways.

Interviewees identified several kinds of dependencies among CRVD strategies/mechanisms: surrogacy, combination, and balance. Some observed that a similar but less effective strategy could serve as a surrogate solution when the more effective strategy is not feasible, e.g., if you can’t increase Ventilation, add Air Filtration, or if you can’t increase distance between passengers (Seating Configuration), add Barriers). Others pointed out that in some cases two things are better than one, e.g., Ventilation plus Air Cleaning, or the result of two things is greater than their sum, e.g., “Good solutions are a combination of materials and cleaning”; “Ads or announcements over the PA systems [in combination with PPE Provisioning] could encourage good behaviors.” An example of balancing is determining whether a higher-efficiency filter (in terms of trapping more particles) would sacrifice airflow speed to the point that a lower-efficiency filter would actually be optimal in terms of maximizing Air Exchange and Air Cleaning. Some also pointed to dependencies between policies and design strategies, e.g., interviewees agreed that most CRVD strategies would become more important if there were no mask mandate on pooled and shared modes.

A theme among concerns raised across many categories was the possible introduction of additional hazards, such as outdoor air pollution from enhanced Ventilation, unknown chemicals and accidental UV exposure (Onboard Surface Sanitization), ozone (Air Cleaning by ionization), more COVID fomites (Barriers if not cleaned), VOCs (PPE Provisioning of hand sanitizers), and accumulation of other organisms (use of cardboard, Hygienic Materials). Another common theme was doubt about the feasibility of implementing some strategies that would require increased maintenance and quality control measures (e.g., Air Cleaning and Onboard Surface Sanitization), passenger compliance and/or enforcement measures (e.g., Occupant Screening and Monitoring and Seating Configuration: eliminating seats through signage). One expert explained, “You need to balance what’s best with what’s accomplishable”; and another, “Best of course are interventions that don’t require repeated individual behaviors” (this could apply to passengers and operators/employees).

Even though there were clear priorities among interviewees regarding most effective CRVD categories and mitigation mechanisms to address COVID-19, most strategies were generally popular and perceived to be desirable outside the context of the current pandemic, except barriers between passengers and occupant screening and monitoring. For example, everyone approved of better vehicle hygiene and many pointed out that it could help reduce transmission of other infectious diseases.

Limitations

The CRVD categories are intended to be exhaustive and mutually exclusive. However, additional categories may emerge as more design strategies are proposed and implemented. There are also a couple areas of overlap among the categories, such as automated hand sanitizer dispensers and touchless trash cans, which fit in both PPE Provisioning and Touchless Technology categories.

Functional interactions and complementarities between different categories and between design and other types of strategies (e.g., policy) are not addressed in the CRVD Typology, though some are discussed in the interview analysis. For example, signage (Communication & Monitoring) communicates policies to riders, which may be in service of other types of CRVD strategies, e.g., designating a seat as off-limits (Seating Configuration). The typology could be expanded to include policies and service app/website features related to each category to support a more holistic approach to risk-mitigating pooled and shared mobility service design.

Some concepts that design firms are pitching include a composite of strategies that cut across multiple CRVD categories. The typology breaks down these design concepts into discrete strategies, but operators may be procuring them as packages. Examples include a three-seat row design for planes with pod-like seats (Barriers) with the middle seat facing backward (Seating Configuration), and a flexible seating configuration for trains with seats that fold up beneath bike racks to temporarily repurpose the seat space (Seating Configuration) as micromobility storage (Multimodal Support).

It is important to note that the applicability and value of any given category or specific strategy may vary between vehicle and service types, since baseline conditions vary. In the interest of surveying the breadth of vehicle design strategies available across all pooled and shared travel modes, this research did not delve into distinctions between vehicle and service types. Again, some of the interview insights shed light on these issues, but they are not addressed systematically in this research.

Limitations of our interview research include potential response biases that are a threat to most interview methods. For example, some interviewees may have been more positive about strategies if they thought we wanted them to approve. To try to prevent this, we stressed that these were strategies proposed by others, not us, and that we were interested in what they thought would be more or less effective. Expert interviewees almost universally qualified their expertise despite strong competencies in related fields. For example, space conditioning experts all focused on building HVAC in their own research and had relatively less knowledge of vehicle HVAC systems. Medical and health experts stressed that our understanding of the pandemic is still evolving and there is a lack of evidence base for many of these strategies, particularly in terms of evaluating clinical impacts of real-world applications as opposed to lab studies.

Conclusion

This research developed a COVID-19 Risk-mitigating Vehicle Design (CRVD) typology to summarize and analyze the wide variety of vehicle design strategies that have been implemented or suggested to reduce the risk of COVID-19 transmission among workers and passengers in shared and pooled vehicles. Public transit and shared mobility service operators can use the CRVD typology as a reference and guide to aid decision-making, in their continued response to the pandemic as well as for future planning. The typology also serves as a launching point for further innovation and research to evaluate the effectiveness of CRVD strategies and their relationship to user preferences and travel behavior, again both within and beyond the current context.

This research also explored layperson and expert perceptions of the identified CRVD strategies. By combining these perspectives, we can create a holistic frame to start to piece together optimal vehicle design solutions that would be both objectively effective in preventing COVID-19 spread and make travelers feel safe. Ultimately, our hope is that this research can help support a safe return to shared and pooled travel in the wake of the pandemic and contribute to a better—more equitable, sustainable, and enjoyable—mobility future.

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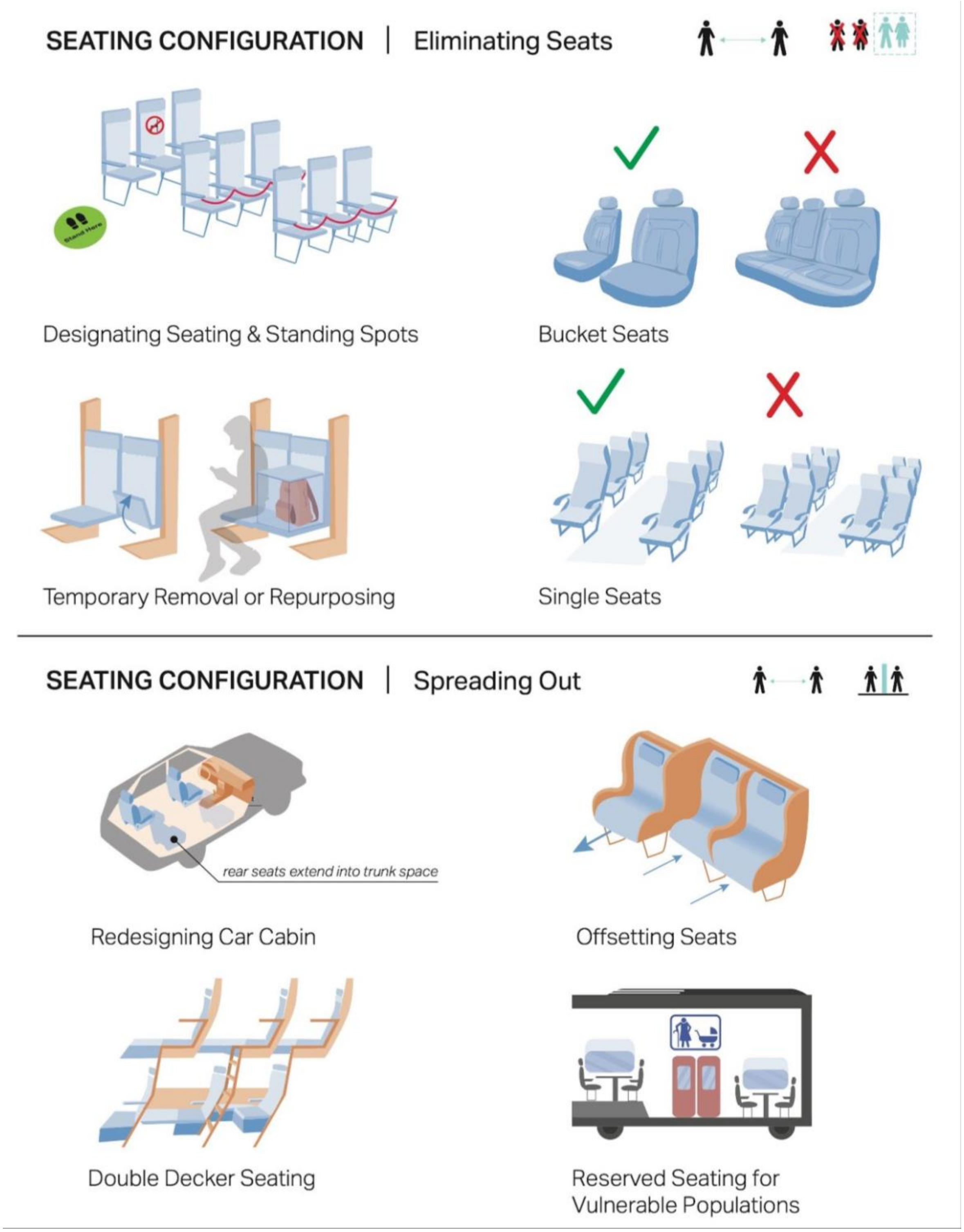
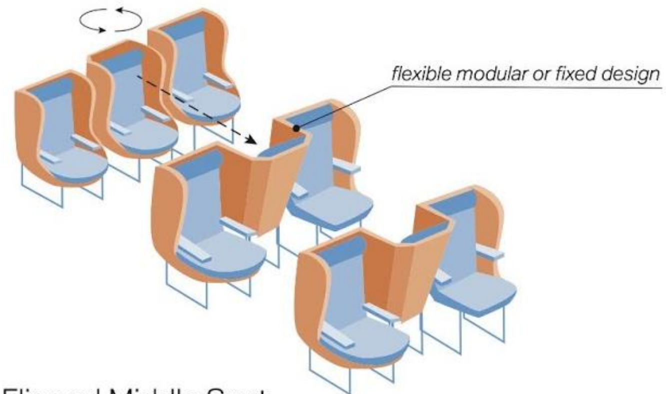
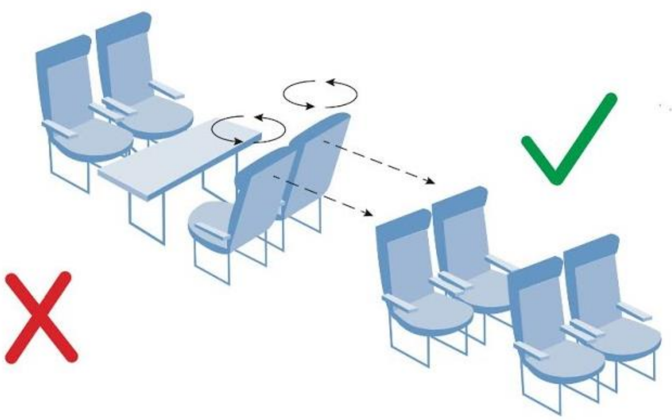
Appendix


SEATING CONFIGURATION | Eliminating Seats
Designating Seating & Standing Spots
Bucket Seats
Temporary Removal or Repurposing
Single Seats
SEATING CONFIGURATION | Spreading Out
rear seats extend into trunk space
Redesigning Car Cabin
Offsetting Seats
Double Decker Seating
Reserved Seating for Vulnerable Populations

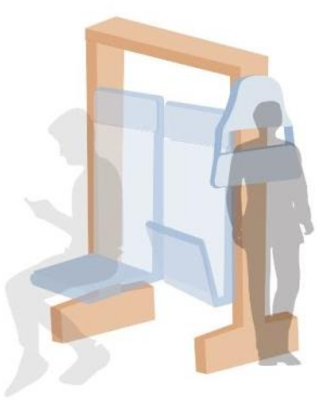
SEATING CONFIGURATION | Reorienting



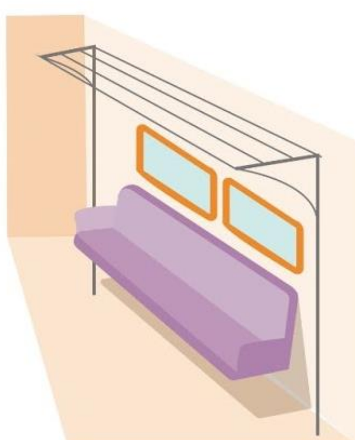
Flipped Middle Seat



Flipping Rows to Face Same Direction (Getting Rid of Tables)



Back Rests for
Standing Passengers

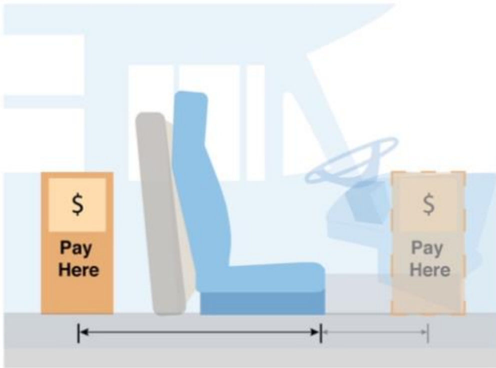


Longitudinal Bench Seating

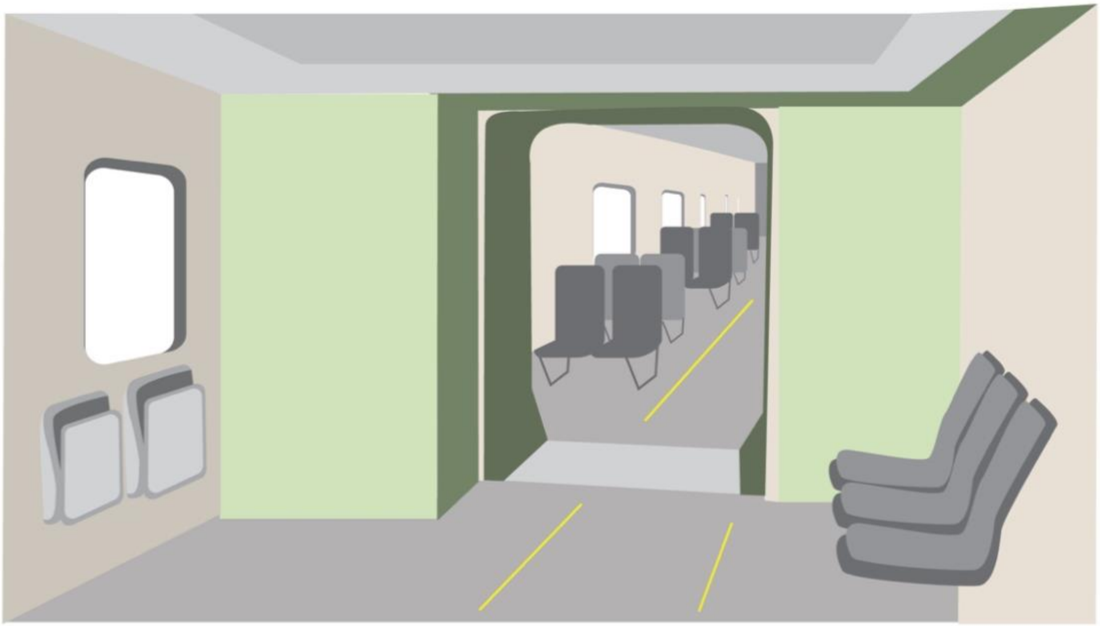
Pathways

One Way Paths

Rear Door (De)Boarding



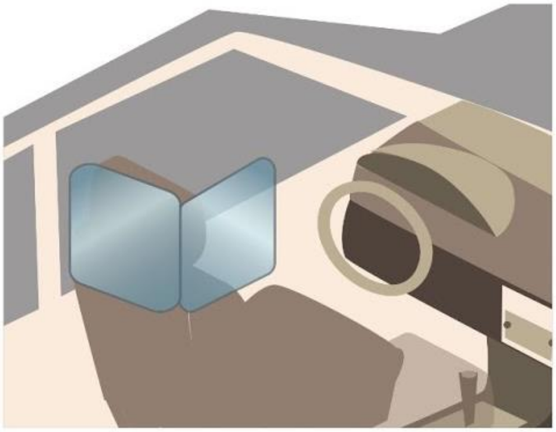
Moving Payment Methods Further From Operator



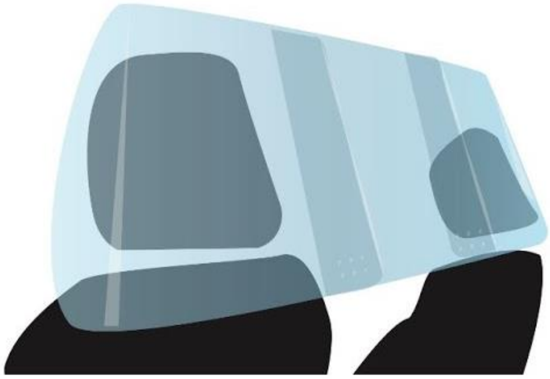
Open Gangway Layout

BARRIERS | Protecting Transit Workers

Cashier Shield



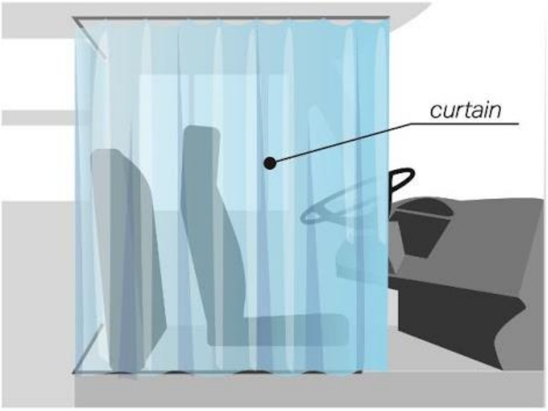
Driver Face Shield



Driver Row Shield

Driver Seat Shield

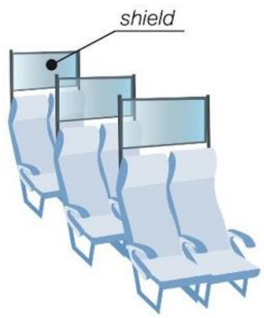
Driver Full Shield



Driver Floor-to-ceiling Curtain or Shield

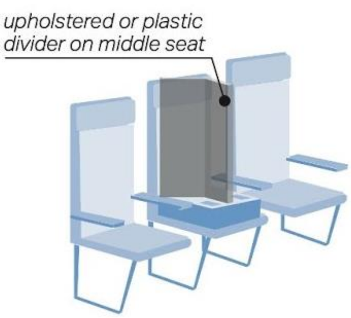
BARRIERS | Protecting Passengers

Passenger Face Shield

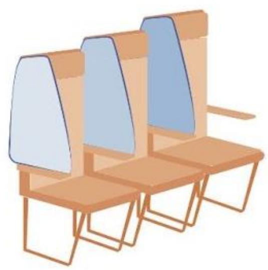


Passenger Row Curtain or Shield

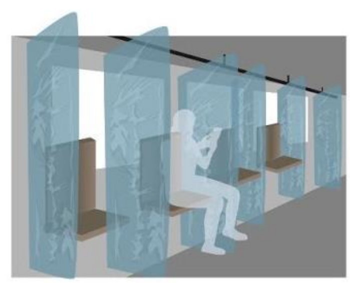
Floor-to-ceiling Shield



Seat Divider

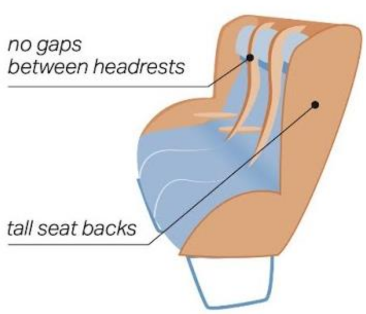


Passenger Seat Shield



Passenger Full Curtain

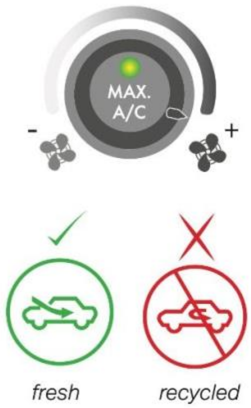
Seating as Barriers



Seatbacks as Barriers

Pod Seats

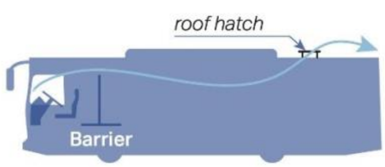
VENTILATION & AIR CIRCULATION



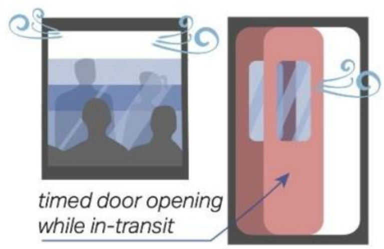
Fresh Air HVAC Setting

Head Rest Air Vent

Fresh Air Ventilation System

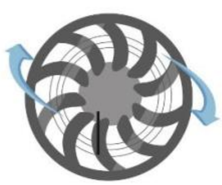


Bus Ventilation Strategy

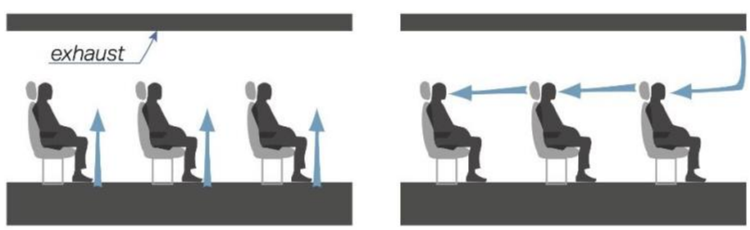


Open Windows & Doors

Open Air Shuttle

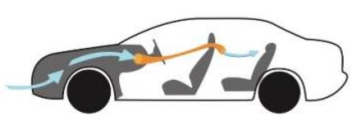


Exhaust Fan

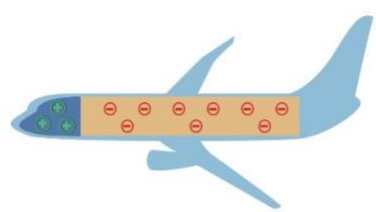


Indirect Airflow

Close Driver Air Outlet

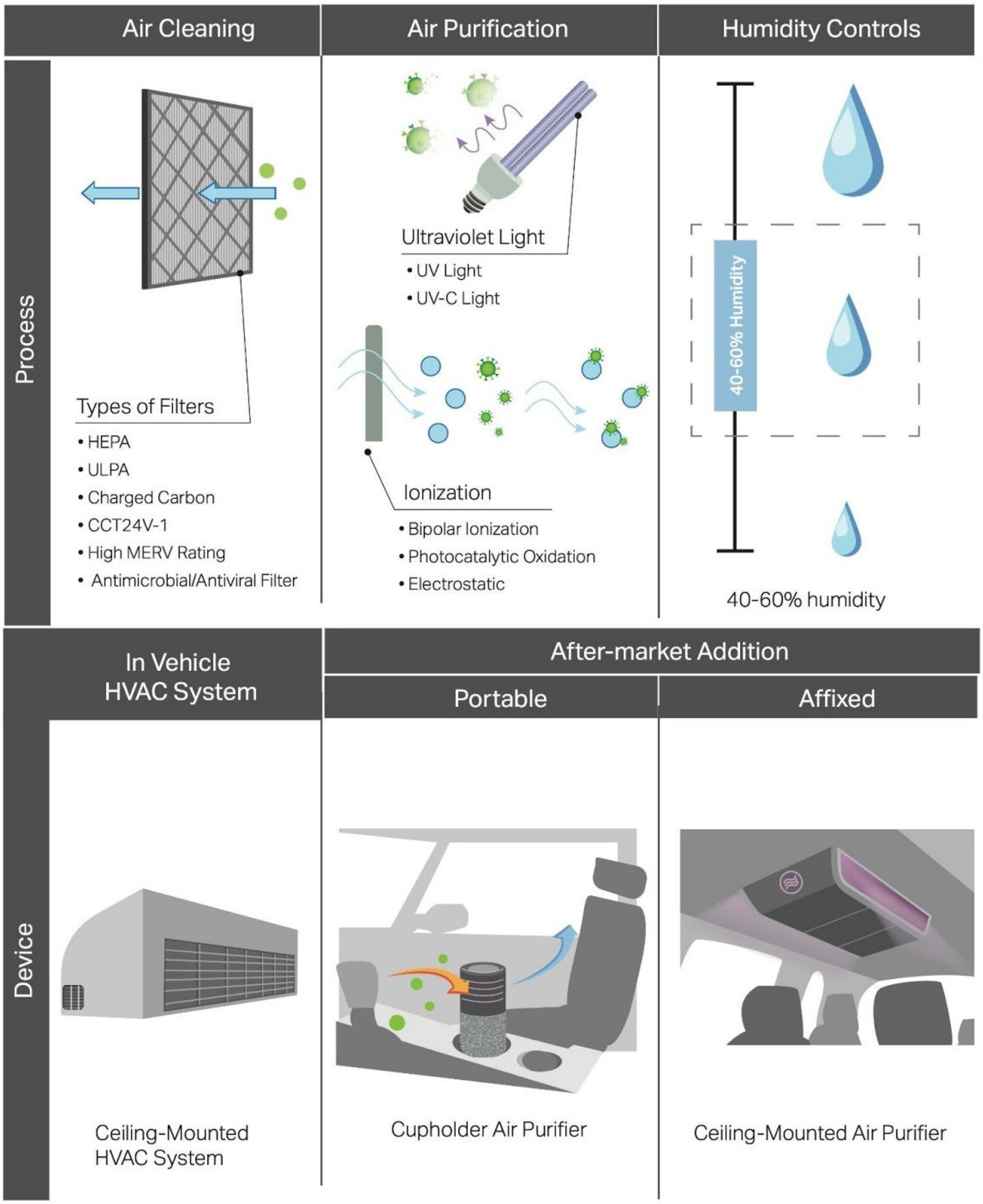


Pipe Air to Backseat

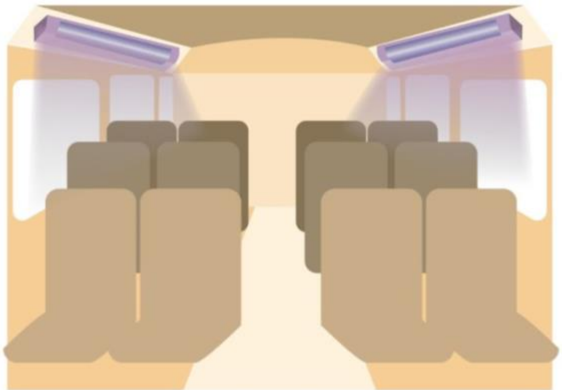


Cockpit Pressurization

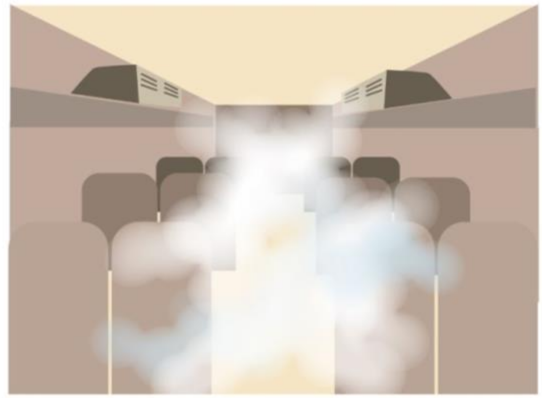
AIR FILTRATION & CLEANING



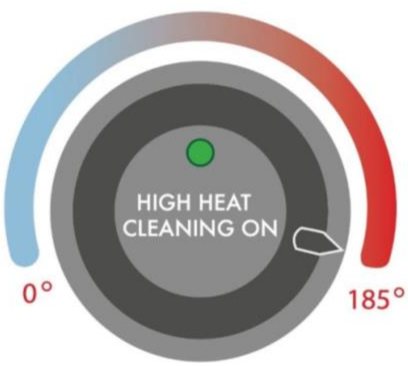
Onboard Surface Sanitization



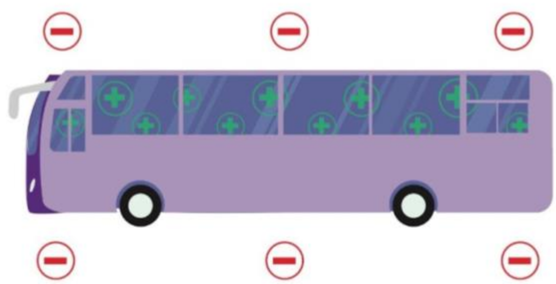
Light UV or LED Lamps



Chemical Onboard Fogger



Heat HVAC High Heat Setting

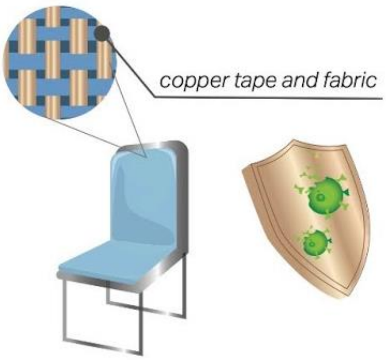


Air Positive Pressure

HYGIENIC MATERIALS

Biocidal Materials

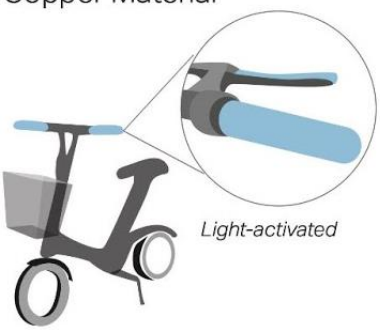
Disposable Materials



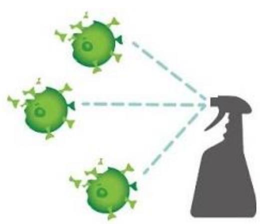
Copper Material

Germicidal Paint

Seat Coverings



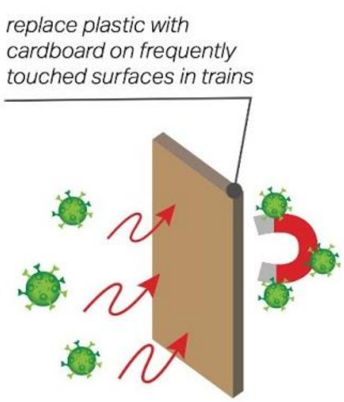
Self-cleaning Handles



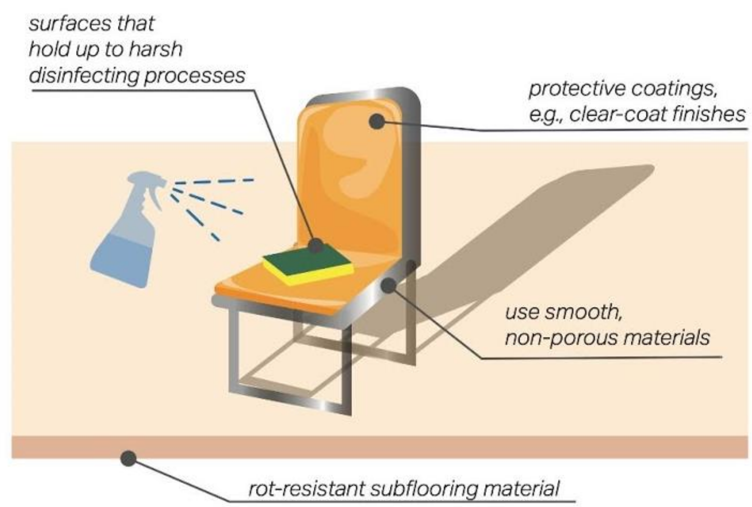
Biocidal Coatings

Floor Coverings

Cardboard

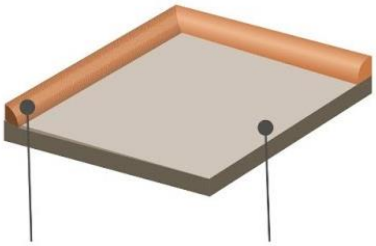


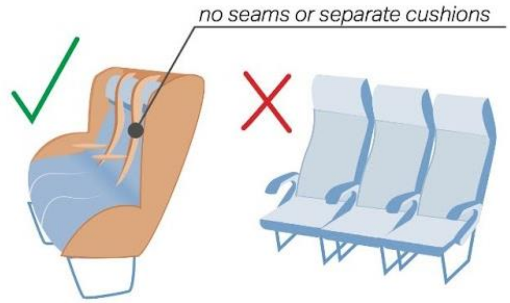
Easy-to-clean & Durable Surface Materials



Hygienic Construction

Minimal Joints and Seams

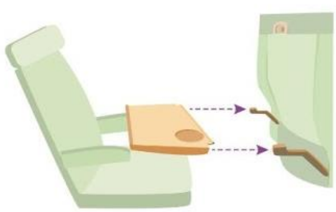


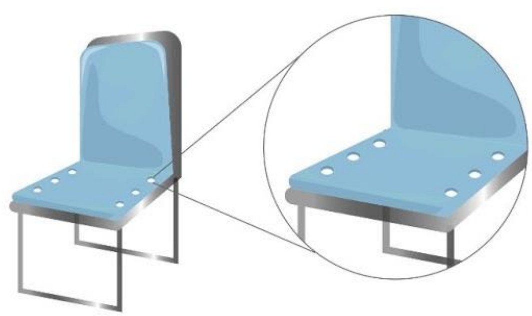


Sealed Floor Seams   Non-ribbed Flooring   Gapless Seat Upholstery

Construction to Accommodate Cleaning

Space for Equipment to Come Onboard   Floor-mounted Piping   Cantilever Seating



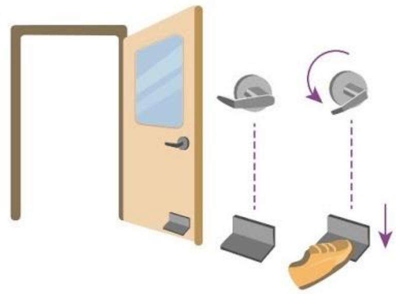


Detachable Food Trays   Drilling Holes in the Bottom of Plastic Seating

TOUCHLESS TECHNOLOGY

Low-Touch Mechanical

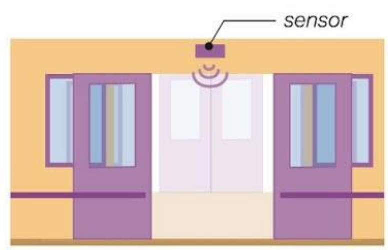
Food Tray Pedal



Door Open Pedal

Automation

Driverless Vehicles



Automated Doors

Automatic Wheelchair Securement

Automatic Hand Sanitizer Dispenser

Ticket Scanners

Personal Props

Personal Device Mount

Personal Handholds

Personal Bag Hook

PPE Provisioning

Disinfectant Wipe Dispenser

Hand Sanitizer Dispenser

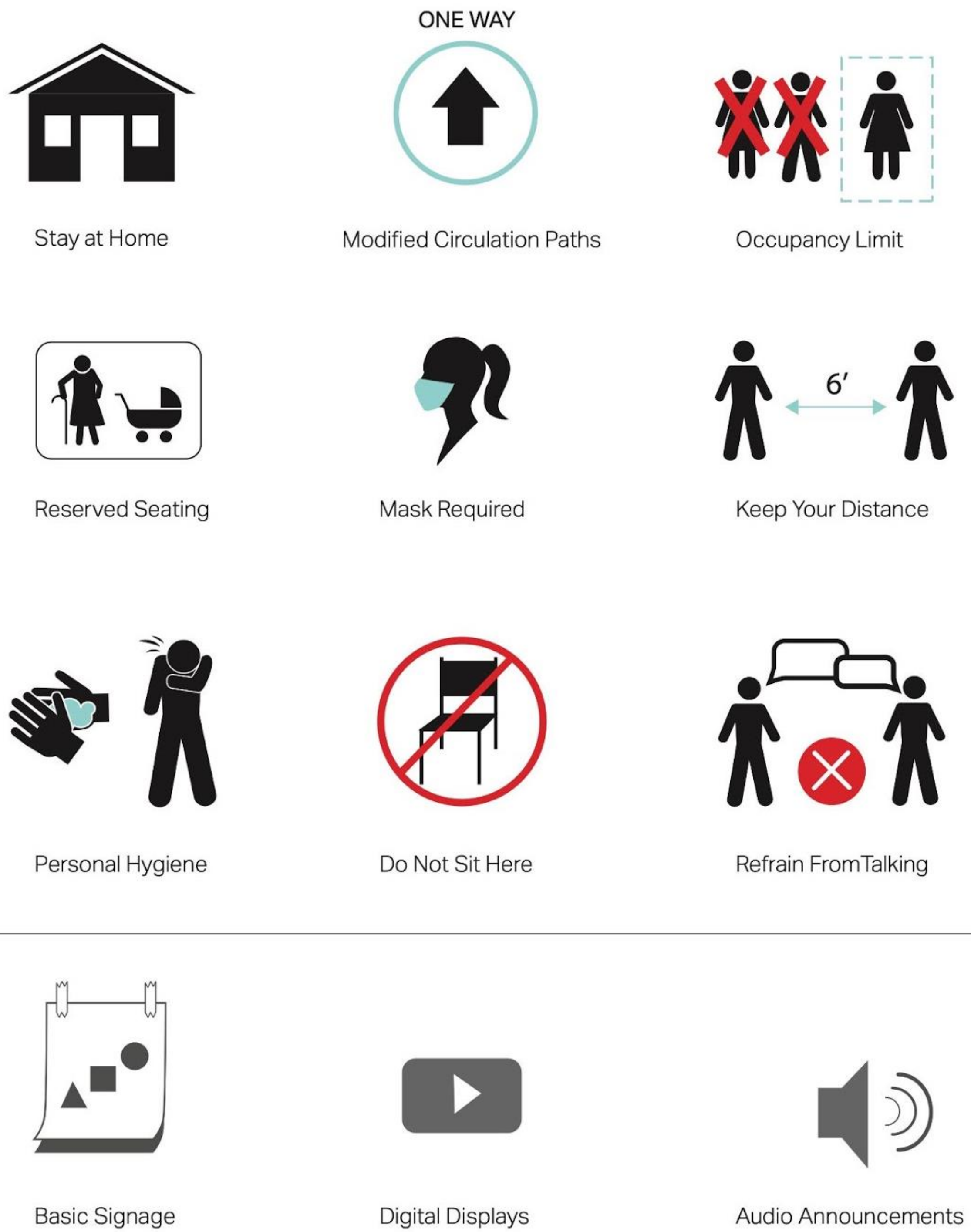
Hand Soap & Adequate Bathroom Supplies

Installed Mask Dispenser

Trash Cans

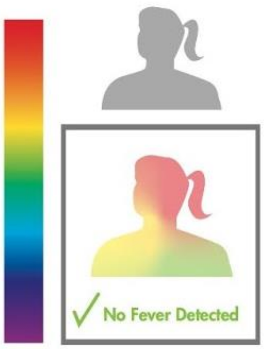
COMMUNICATION & MONITORING

Education and Prompts



COMMUNICATION & MONITORING

Symptom Detection & Contact Tracing



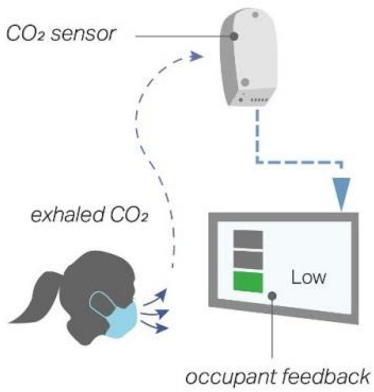
Thermal Imaging Camera

QR Code

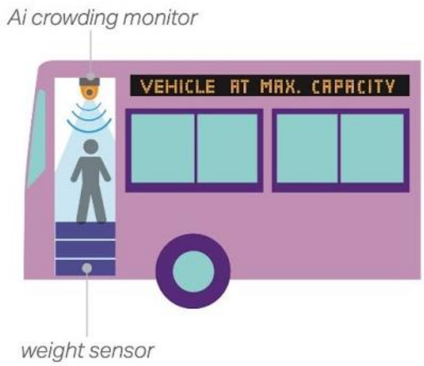
Facial Recognition Cameras

Environmental Feedback

Color Changing Seats



CO_2 Monitoring/Feedback

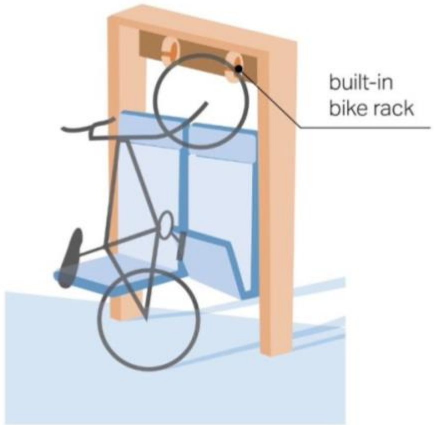


Occupancy Sensors & Feedback

MULTIMODAL SUPPORT

Bus Bike Rack

Car Bike Rack



Flexible Bike Storage on Train