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VERSION 1.1

Airflow and elevators

Highlights of an airflow study conducted to determine the relative risk of exposure to COVID-19 among elevator passengers

OTIS

Executive summary

Elevators play an essential role in keeping people around the world on the move, every day. However, the global COVID-19 pandemic has created some concerns around the relative risk of infection in shared common spaces, including elevators. Early in the pandemic, stories began appearing in both popular and scientific publications, raising questions about riding in elevators, based on the understanding of airborne transmission as a critical means of disease spread and, at least in part, the misperception that elevator cabs are sealed spaces with limited airflow.

Elevators are, in fact, well-ventilated spaces. By code, elevators are required to have openings for ventilation. Together with fans that are commonly present in elevators, these openings provide a high level of air exchange. Exposure time to the air and other people in an elevator is also limited due to the short duration of the elevator ride – less than two minutes on average for the highest rise buildings and on the order of 30 seconds for many rides. While this knowledge and a simple analysis suggest that airborne transmission of aerosols and particles in elevators is much lower compared with many other common spaces, it does not take into account the dynamics of specific situations including passenger flow, ventilation rates, cab sizes and mitigation strategies including masks and air purification.

Every elevator riding scenario is different, with multiple variables that are important to the movement of people, air and elevators. To understand the impact of these dynamics and support our customers and the riding public with science-based information and solutions, Otis commissioned a three-month elevator airflow research study. The study focused on understanding the relative risk of COVID-19 exposure in elevators. We set out to answer questions around how mitigation strategies impact how using elevators compares with other situations in which we find ourselves. More specifically, the research team undertook the study to:

- Evaluate transmission risk of airborne particles infected with SARS-CoV-2 (the virus that causes the disease COVID-19) when taking an elevator
- Study different elevator design parameters – including fan speed – that could have a major impact on the exposure risk
- Identify the impact of mitigation strategies and methods
- Compare the exposure risk of an elevator with other enclosed spaces, such as an office or a city bus

The research was led by Dr. Qingyan (Yan) Chen, the James G. Dwyer Professor of Mechanical Engineering at Purdue University, who is widely recognized for his research into the spread of infectious disease through indoor air systems – and how to prevent it. Dr. Chen and his team worked closely with the Otis team.

The investigation used state-of-the-art multizone modeling to simulate airflow between zones across the envelope of a building, and computational fluid dynamics to simulate particle dispersion during a two-minute elevator ride compared with time spent in other common spaces. For the elevator ride we modeled multiple scenarios, including particle dispersion when the doors open as passengers get on and off the elevator.

Coupled with what we already know about elevator design and operation, the findings of the study show that riding in an elevator is a relatively low-risk activity. The research has shown that the higher the level of air exchange, such as that provided by higher-flow elevator fans, the lower the exposure risk. When considering relative risks between common indoor activities, the study found that the elevator ride is comparable to a short time in an office or bus. However, when you consider the longer average duration of a stay in a bus or office compared to an elevator ride, we observed significantly less relative exposure risk in an elevator.

In addition, mitigation strategies were shown to reduce the risk even further. Proper mask usage cut the potential risk in half, air purification via needlepoint bipolar ionization (NPBI) reduced risk 20-30% and combining the two strategies resulted in a 60-65% reduction in relative exposure.* While the calculations themselves don't vary, the results of the calculations do vary depending on ride time and riders' positions in the elevator.

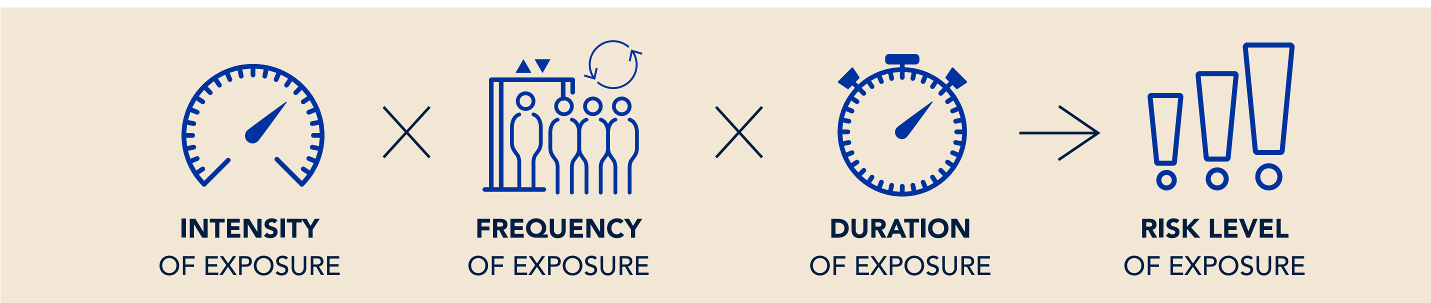
This study and its findings are just one part of the Otis commitment to keeping elevator passengers well-informed throughout the COVID-19 pandemic and into the future. We are continuing to support our customers with both behavioral guidance and multilayered technology solutions, and we're dedicated to pursuing additional research to enhance our collective understanding of risk.

Proper mask usage cut the potential exposure in half, air purification via needlepoint bipolar ionization (NPBI) reduced risk 20-30% and combining the two strategies resulted in a 60-65% reduction in risk.*

*For comparison details and more information, see page 16

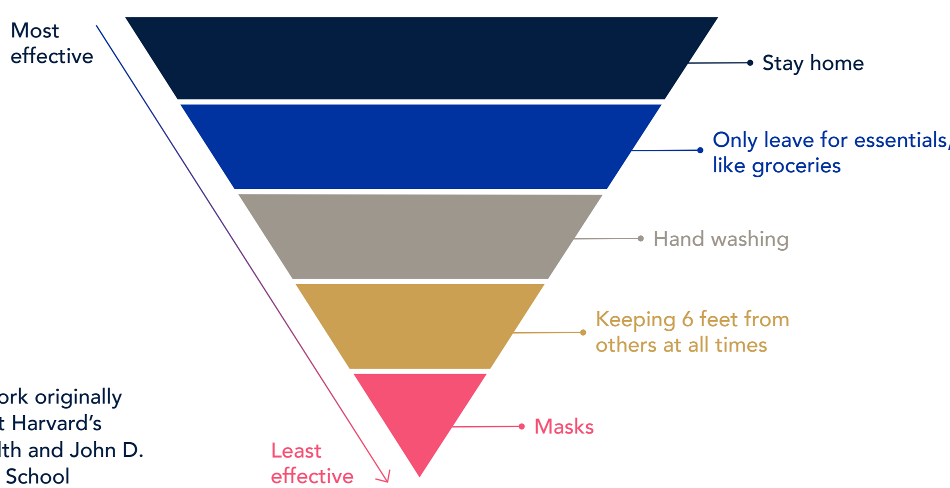
Assessing risk and the novel coronavirus

As the world continues to navigate the COVID-19 pandemic and societies look for ways to resume aspects of everyday life, experts across disciplines recognize that there is no "silver bullet." A risk-based approach, informed by science, is needed to recommend reasonable control measures for each situation (Defile, 2020). Risk level is based on the **intensity, frequency and duration of exposure**. For each application the level of exposure via airborne means or physical contact may be different. Not all applications can be easily compared without using a combination of techniques and different disciplines.



Through a risk-based approach, we are able to determine and prioritize elements of a layered strategy that encompasses both behavioral and technology recommendations, each with varying levels of effectiveness and disruption.

HIERARCHY OF CONTROLS AS APPLIED TO SARS-COV-2



Adapted from controls framework originally proposed by Joseph G. Allen at Harvard's T.H. Chan School of Public Health and John D. Macomber at Harvard Business School

These broad principles are applicable in the case of elevators. As we look to address concerns around the relative risk of exposure in an elevator, several factors and scenarios need to be balanced to achieve a range of positive outcomes and solutions for our customers and the riding public. We need to account for the dynamics of not just the elevator but the building environment and people's behavior. Understanding relative risk and how to integrate different layers of control methods and solutions are key.

Behavior

- Physical distancing & guidance
- Virtual & remote work

Technology

- Touchless technologies
- Passenger communications
- Purification & hygiene
- Monitoring & tracking

When considering responses to the current pandemic, these solutions primarily focus around four key areas:

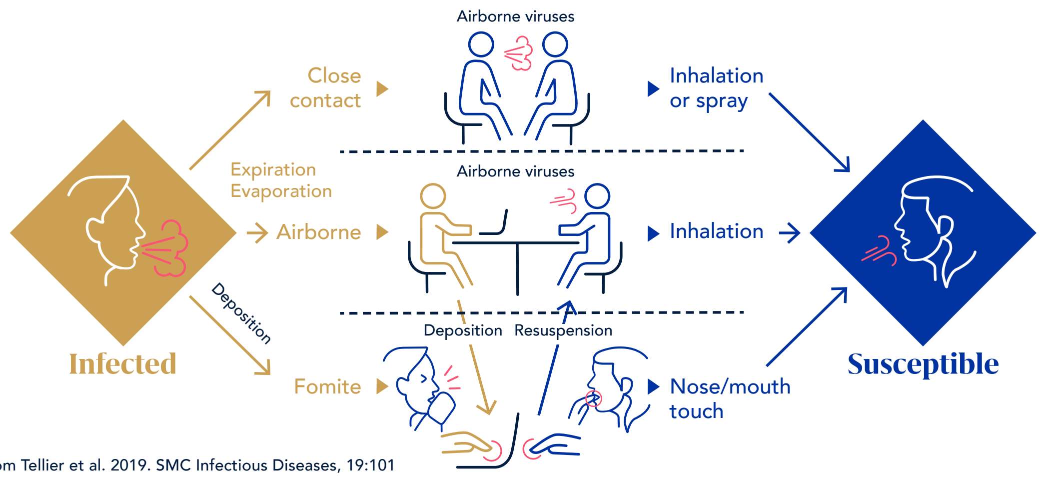
- People and elevator movement
- Guidance for safe riding
- Exposure risk mitigation
- Advanced technology solutions

Additional considerations are driven by the vertical movement of the elevator, the opening and closing of doors, and the movement of people in and out of elevators, all within a reasonably small enclosure volume. Further, these factors must be viewed in the context of what science tells us about how COVID-19 travels through the air.

EXAMINING COVID-19 TRANSMISSION

The World Health Organization (WHO), Centers for Disease Control and Prevention (CDC) and other experts indicate multiple modes of transmission for the novel coronavirus, SARS-CoV-2, which causes the disease COVID-19.

Emerging science and evidence seem to support that airborne transmission may be more critical than surface-to-surface transmission (WHO and Mandavilli, 2020). With the increasing emphasis on airborne transmission, the emphasis on indoor air quality and airflow continues to grow.



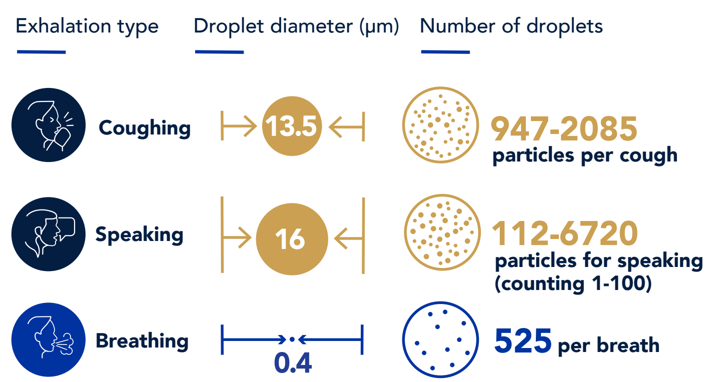
Adapted from Tellier et al. 2019. SMC Infectious Diseases, 19:101

Airborne transmission either via large droplets or small aerosols depends on the particle size and the amount inhaled. Different quantities of particles are exhaled during different situations. Breathing spreads fewer but smaller particles than speaking, and speaking may spread larger particles than coughing. The amount of time spent breathing, coughing or speaking is important, as well as the distance and duration spent in close proximity to an individual and the airflow of how the particles move in space. The intensity of the exhalation, duration you are in proximity to an infected individual and frequency of contact may all contribute to the relative risk of infection spreading.*

It is not just the number of particles in the air, but the impact of where these particles go and whether they are inhaled and rest either in the upper or lower parts of your lungs. We can model the particles and air, but we also need to take into account the relative accumulated dose of the particles for an individual in different scenarios. It is not necessarily sufficient to study airflow alone, but understanding the concentration and distribution of the potentially infected particles dynamically at different times in different situations gives us a more accurate assessment of risk.

Many quick analyses may look at perfectly mixed air and simplify the situation. However, analyzing the movement of the air, the movement of the people and the movement of the elevator together provides more detail. For a complete analysis, further work could include detailed study of surface-to-surface or fomite transmission.

There are multiple ways to analyze airborne transmission and the spread of the virus using techniques from public health and medicine, engineering, mathematics and statistics, network theory and many more fields.



Based on Chao et al. 2008. Aerosol Science 40:122-133

*A recent study shows that virus concentration is different in various sized particles. For example, virus concentrations are typically higher in the finer particles generated deep within the lungs and throat, which can be expelled through coughing. Conversely, particles generated from speaking mainly consist of saliva, which can contain lower virus content.

Understanding elevators

In examining the relative risk of COVID-19 exposure in elevators, the science around airborne transmission of particles points us to a focus on airflow. Though relatively small, modern elevator cabs are well-ventilated spaces with systems for circulating the air frequently.

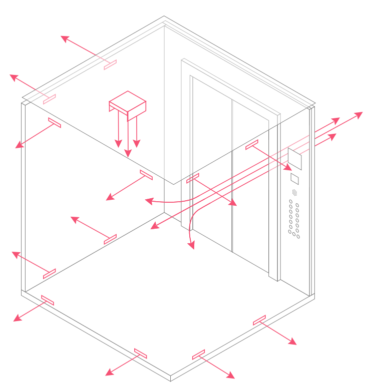
- By code, **openings for ventilation are required for all elevators**
- **Exposure time is minimal** due to a short average cab ride
- Elevators have a **high level of air exchange, lowering exposure levels**

Elevators have required ventilation standards. By code, openings are required for natural convection, and the majority of elevators have fans or can easily be retrofitted to have fans. Elevator fans are often sized to provide one air change per minute – or 60 air changes per hour. Air changes per hour (ACH) are a measure of the air volume added to or removed from a space in one hour, divided by the volume of the space. Higher values correspond to better ventilation.

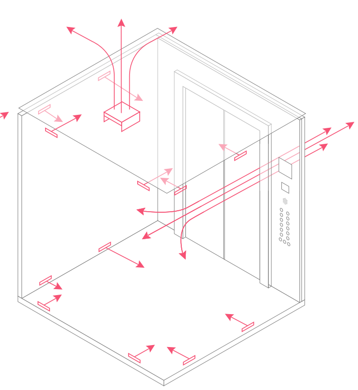
By North American elevator code, cabs must provide 3.5% of the platform area as ventilation openings for convection purposes (American Society of Mechanical Engineers, 2019). European code EN81-1, which is applied in much of the world, requires 2.0% ventilation, still a significant amount of opening regardless of cab configuration (British Standards Institution, 2014).

A SYSTEM WITHIN A SYSTEM

When considering an elevator ride, we consider the air and space the passenger encounters in the elevator cab itself, the hoistway or shaft in which the elevator travels, and the other parts of the building where people are moving. The opening for the fan and the opening around the doors may be included in the calculation. These openings provide inlets and outlets for convective transfer of passive airflow and aid when more active ventilation is present. Depending on the complexity of the building, additional factors including pressurization, fire considerations and more sophisticated HVAC systems should also be considered, as well as air movement between the elevator and the lobby or floors at different stops.



Inlet configuration



Exhaust configuration

Study overview

An understanding of elevator systems, ventilation and design, along with the nature of COVID-19, suggests that the relative exposure risk in elevators is lower compared with many other common spaces. However, it does not take into account the dynamics of specific situations including passenger flow, ventilation rates, cab sizes and mitigation strategies including masks and air purification.

To understand the true impact of these dynamics, Otis commissioned a team at Purdue University to conduct a study focused on understanding the relative exposure to COVID-19 in elevators. The study focused on airflow and investigated the impact of ventilation rates and types, purification technologies and interventions including masks in elevator environments.

Ventilation rate

Ventilation type and the direction the fan blows

Cab configuration, studying the most popular cab sizes with some variations

Impact of **proper mask usage**

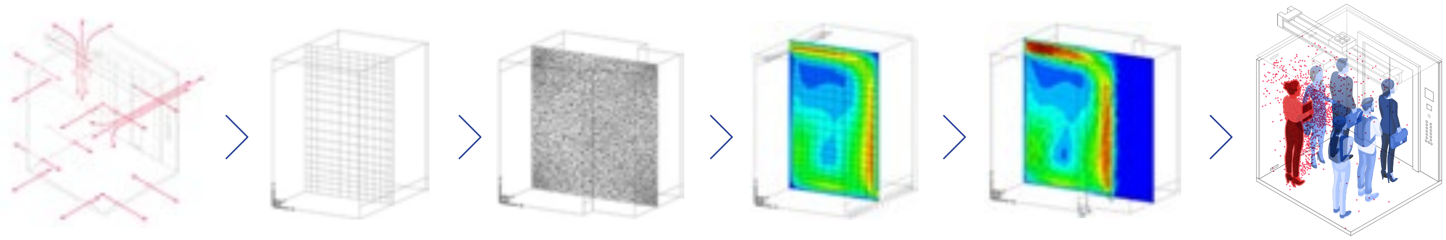
Impact of **purification technologies**, specifically needlepoint bipolar ionization (NPBI)

INTRODUCTION TO AIRFLOW MODELING

Airflow is complex. It can be modeled in a computer and by measuring actual airflow in an experiment. In order to study multiple scenarios and variables quickly, computer modeling is often recommended. The computer modeling and numerical simulation methods used in this study are at the cutting edge in the state of the science.

For a single enclosed space, computational fluid dynamics (CFD) is the most powerful airflow and contaminant modeling tool. CFD has been widely used because it can provide informative and accurate results of transient particle transport in enclosed environments. There are two parts of CFD modeling on contaminant transport: airflow modeling and particle/particle modeling.

To obtain the information of airflow distribution, CFD numerically solves a set of partial differential equations for the conservation of mass, momentum (Navier-Stokes equations), energy and turbulence quantities. The solution includes the distributions of air velocity, pressure, temperature, turbulence parameters and contaminant concentration.



Geometry & assumptions → **Computer model with finite volume mesh** → **Data transfer between multiple models** → **Air direction & velocity results** → **Multiple scenarios considered** → **Particles visualized & result quantified**

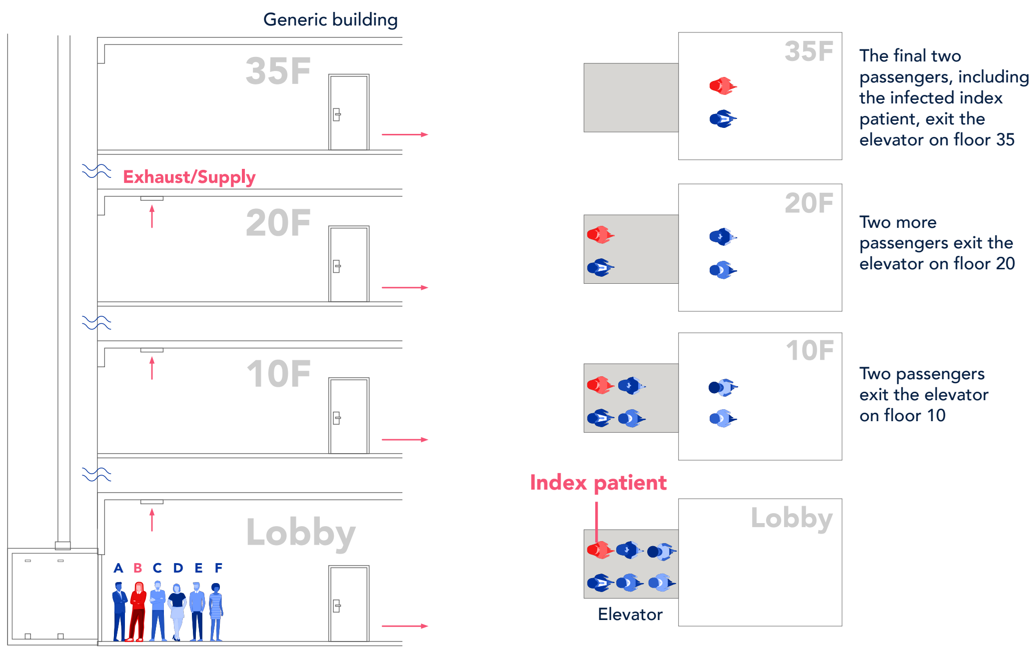
To best simulate the elevator environment, we used a multizone model, as it is applied to multiple rooms connected with openings such as doors, windows and cracks. The multizone models also assume each zone to be a well-mixed space. Although the assumption that uniform air contaminant concentration in a zone may not be valid, it is sufficient for simulating airflow through cracks between an elevator cab and hoistway and between hoistway and lobbies. This is because the uncertainties in those large spaces are very high. The airflow through the small openings is more important than the uniformity of virus concentration distribution.

The Reynolds-averaged Navier-Stokes (RANS) models are the most popular CFD models. RANS models solve the mean air variables, such as air velocity, air temperature, etc. and model turbulence properties by solving turbulence transport equations. For indoor airflow modeling, Zhang et al. (2007) recommended the RNG k-ε model after reviewing and comparing many models. The model was selected for the present study.

Although this research did not include experimental measurements, the numerical simulation technique was based on validated tools. For example, we used the Lagrangian model in CFD to simulate particle dispersion in a clean room (Murakami et al., 1992). We also compared the simulated and measured particle concentration distributions. The results of Lagrangian calculation were based on a sample size (i.e., the number of trajectories) of 100,000. The results are in reasonable agreement with the experimental data. The Lagrangian particle tracking method could introduce uncertainty into particle concentration calculations. When the particle number is low, the predicted particle concentration may not be a stable solution due to the random factors used in the model. This could be seen in the results obtained in this project.

STUDY MODELING METHODOLOGY

Using the multizone computer modeling and numerical simulation methods outlined above, the study set out to examine potential exposure risk by simulating various elevator ride experiences. To consider the whole process when taking an elevator, we assumed an elevator ride scenario in a commercial building with 35 floors. Among the six riders, two riders left the elevator on floor 10, another two left on floor 20 and the other two on floor 35. One of the two to floor 35 was an index patient, shown by the red color in the following figure. The longest trip took about two minutes. This typical building and representative elevator journey allowed us to isolate variables and determine that the exact details of elevator speed or path were not as important as total time in each space.



This investigation used the multizone model, ContamW, to simulate airflow through cracks between an elevator cab and hoistway and between hoistway and lobbies. The results of the multizone airflow modeling were used as a part of the thermo-fluid boundary conditions for detailed simulations of COVID-19 virus particle transmission for the elevator ride. The detailed simulations used the previously described CFD technique with the Lagrangian method for particle dispersion. The simulations of the two-minute elevator ride were further divided into eight sub-cases for considering the changes of flow domains in the elevator ride. The particle and airflow distributions of the previous sub-case were used as initial conditions of the current sub-case to ensure smooth transfer of the data for accurate simulations of particle transmission in the elevator ride. The CFD used was Reynolds-averaged Navier-Stokes equations with RNG k-ε turbulence model built in the ANSYS Fluent computer program. ANSYS Fluent is one of the more sophisticated CFD codes available and is commonly used for advanced computer simulation.

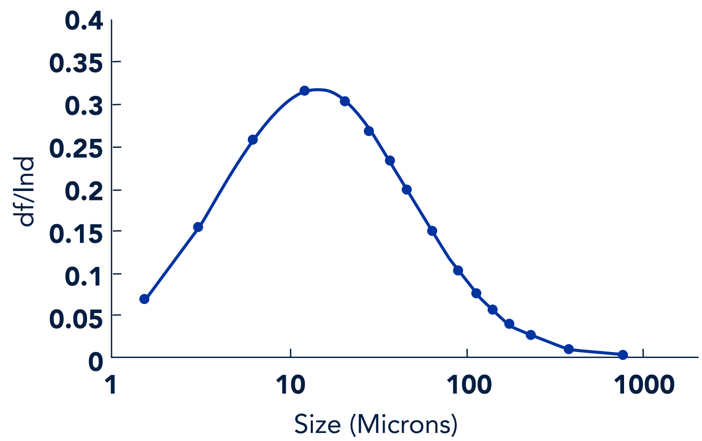
This investigation considered mainly the transmissions of airborne particles that were generated by breathing of the index patient. Each breathing cycle lasted four seconds and generated 525 particles with an average diameter of 0.4 μm. The research also studied a coughing case when the index patient coughed once when entering the elevator.

The impact of different elevator design parameters on the particle transmission was also studied:

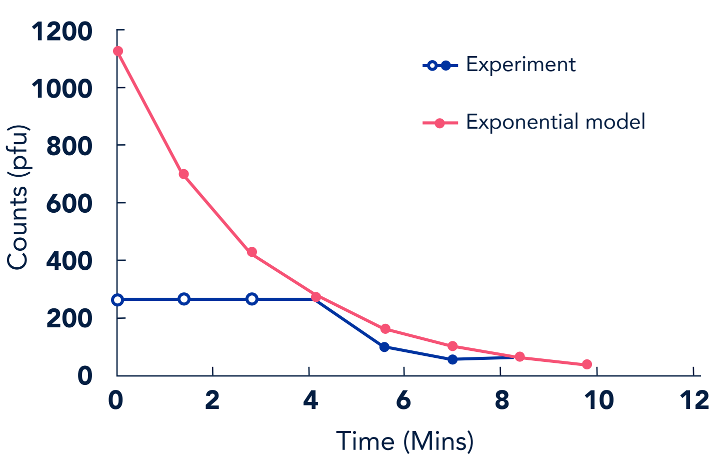
- Ventilation rate of 350 cfm, 150 cfm and 55 cfm and infiltration rate of 36 cfm
- Air blowing in and air blowing out
- Wide elevator cab and deep elevator cab

Since the study used particle number or particle mass inhaled by susceptible riders as the evaluation criterion, it could not show the absolute risk. Thus, we compared the exposure level to the particles in the elevator ride with that in an office and a bus.

This study investigated particle sources generated by an index patient through breathing and coughing. For breathing, the numerical simulation used an average particle size of 0.4 μm in diameter, with 525 particles per breathing cycle. Each breathing cycle lasted four seconds. For coughing, this study used 16 different particle sizes and numbers as shown in the figure below (Chao et al., 2009). The total particle number per cough was 1,951. In addition, flow boundary conditions for breathing through the nose and coughing through the mouth were from Gupta et al. (2011).



Particle size distribution for coughing from Chao et al (2009) study



NPBI efficiency curve

AIR PURIFICATION MODELING

To estimate the accumulated particle dose by each susceptible person, this investigation developed a user-defined function (UDF) to calculate accumulated particle numbers through equations for accumulated particle mass in the breathing zone of each person, which were outputs of the CFD simulation. The breathing zone was a sphere space centered on the nose of each person with a radius of 0.2 meters.

In addition to accumulated particle dose under various rider and airflow scenarios, the study also used modeling to simulate the impact of needlepoint bipolar ionization (NPBI) as an air purification strategy. A similar UDF was developed to model the effect of the air purification.

Study results

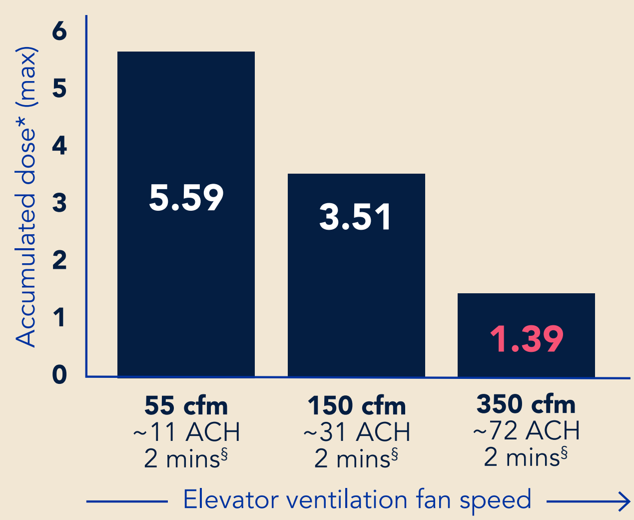
The study findings show that elevator travel is a relatively low-risk activity. The high level of air exchange in an elevator lowers the risk of exposure, showing it to be comparable to a short time in an office or a bus. Mitigation strategies including masks and air purification using needlepoint bipolar ionization demonstrated a further reduction in risk.

VENTILATION AND EXPOSURE

Due to the short duration of the elevator ride, elevators with high ventilation rates represented lower exposure risk. Although breathing generated particles continuously, the number and size of the particles were lower than those from a cough. The accumulated particle mass dose of the susceptible riders for the coughing case can be 6 orders of magnitude higher than those for the breathing case.

The higher the ventilation rate, the lower the accumulated dose could be. However, this was not always the case because in a few cases the nonuniform distributions of the particles could cause a higher dose even with a higher ventilation rate. A deep cab could trap the particles inside the elevator. The air supply direction also had an impact on the particle dispersion in the elevator cab.

The exposure to the particles in the lobby of floor 1 was low in this case because the ventilation of the HVAC system and thermal plumes from the riders would cause the particles to disperse. The movements of the riders could entrain some particles in their wakes. The particle distributions in the elevator cab were highly nonuniform. The person who stood in front of the index patient had the highest exposure, and the person who stood on the side of the index patient had the highest accumulated particle dose due to the longest exposure.



ACH: Air changes per hour measures the air volume added or removed from a space in one hour, divided by the volume of the space. Higher values correspond to better ventilation.

§Study simulated scenarios of 2 minutes to assess maximum risk. Average cab ride is generally <1 minute.

*Accumulated dose is the amount of virus a person is exposed to and depends on intensity, frequency and duration of exposure.

Environmental factors (e.g., coughing, talking, rate of breathing, physical activity, cab configuration, etc.) may impact the overall exposure of an individual.

Results illustrate maximum exposure for riders for 2-minute ride without any mitigation, such as properly worn masks by all riders or added purification/ventilation (see table on next page for average, maximum and minimum results in more scenarios).

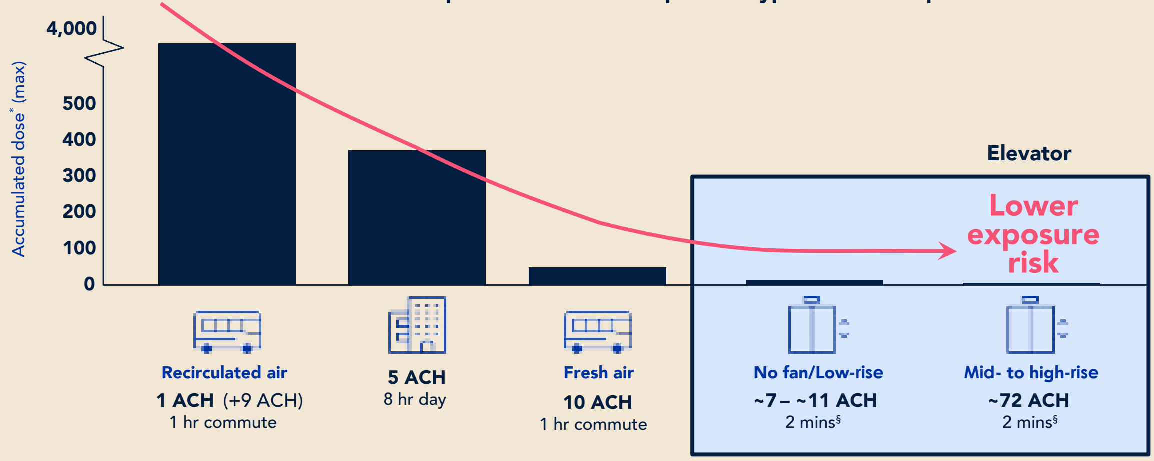
COMPARISONS WITH OTHER ACTIVITIES

To better understand the true nature of the risk in an elevator, the study compared the quantitative results of accumulated dose in elevator scenarios with that in other common spaces and activities associated with office work. More specifically, we examined a bus with varying levels of air quality and an office environment. The focus is on the risk tied to airflow, with air exchange identified as a key factor.

The accumulated particle dose in a well-ventilated elevator with 350 cfm flow was equivalent to spending only four minutes in an office with 5 ACH clean supply air. Even for a poorly ventilated elevator with 55 cfm flow, the dose for the ride was the same as a 15-minute stay in the office. The bus with 10 ACH outside air was relatively low risk, but the bus with 90% of recirculated air posed more than 25 times the risk of the elevator.

When we take into account the duration of these activities, elevators become significantly lower risk by comparison. As noted, the average elevator ride lasts less than two minutes. An eight-hour day in an office or an hour on a bus was shown to yield exponentially higher accumulated doses.

Relative risk of exposure and airflow impact for typical common spaces



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Case	Space	Airflow direction	Flow rate (cfm)	Cab type*	Intervention	Particle source	Accumulated dose Ave.	Max. 6 order higher	Min.
1	Elevator	In	350	Wide	None	Breathing		1.59	1.03
2	Elevator	In	350	Wide	None	Coughing			
3	Elevator	In	150	Wide	None	Breathing		3.51	0.04
4	Elevator	In	55	Wide	None	Breathing		5.59	0.04
5	Elevator	Infiltration	36	Wide	None	Breathing		4.78	0.03
6	Elevator	Out	350	Wide	None	Breathing		4.73	0.01
7	Elevator	In	55	Deep	None	Breathing		13.06	0.17
8	Elevator	In	350	Wide	NPBI	Breathing		1.13	0.03
9	Elevator	In	350	Wide	Mask	Breathing		0.71	0.01
10	Office – 5 ACH	In	970	N/A	None	Breathing	0.62	0.79	0.08
11**	Bus – 1 ACH	In	379	N/A	None	Breathing	0.27	0.83	0
12***	Bus – 10 ACH	In	379	N/A	None	Breathing	80	132	51

*The wide cab was 2.00 m wide, 1.65 m deep and 2.50 m high and had 3500 lb/1600 kg capacity and the deep cab was 1.10 m wide, 1.80 m deep and 2.00 m high and had 1000 kg capacity.

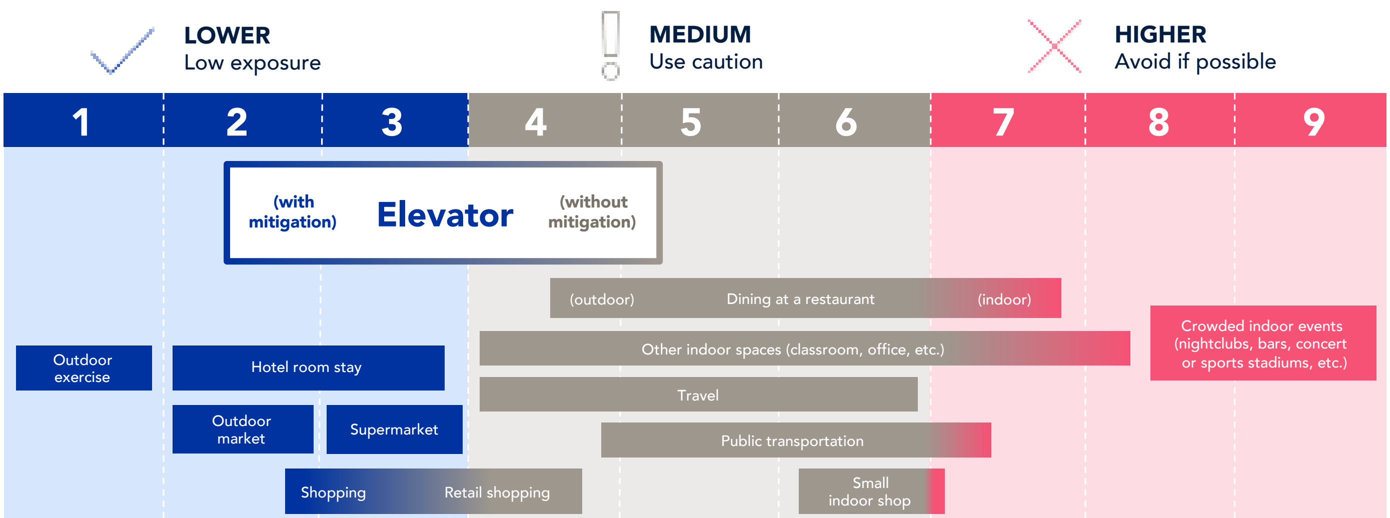
**10 ACH clean outside air

***1 ACH clean outside air and 9 ACH recirculated air

In addition to quantitative results, qualitative comparisons can give us a better sense of the relative exposure risk of riding in an elevator. The table below gives a general sense of where the relative risk of an elevator ride with and without mitigation may fall on a spectrum of other activities. It should be noted, however, that making quantitative comparisons to many different scenarios is difficult.

Even in controlled computer simulations, there can be a lot of variables, and both the natural and built environment have a lot of variation, especially when combined with human behavior. The risk of dining at a restaurant, for example, varies based on number of diners, proximity, time spent in the space and a number of other factors. Similarly, the risk associated with other indoor activities spans the spectrum due to variables related to both the environment itself and the behavior of occupants.

Still, with what we've learned, we can generally place riding an elevator in a relative low to medium risk of exposure, generally safe category comparable to a hotel room stay or outdoor dining, depending on the factors outlined.



Variation of intensity, frequency and duration of exposure contributes to different degrees of exposure even within each activity category
Adapted from relative framework originally proposed by Julie Marcus at Harvard and Eleanor Murray at Boston University
Risk of exposure in elevators can be lowered by applying proper mask usage, air purification (like NPBI), physical distancing, etc.

MITIGATION STRATEGIES

Although the study results show that elevators are among lower-risk indoor spaces for COVID-19 infection, any mitigation methods should be considered. This investigation considered two intervention methods: use of surgical masks and disinfection by needlepoint bipolar ionization.

This study selected surgical masks as an example to study the impact of masks on the accumulated dose of susceptible people. We assumed that the filtering efficiency for exhaled particles from the index patient was the same as that for inhaled particles by the susceptible riders. This investigation used a mean filtration efficiency of 33% for the surgical mask according to Bowen (2010).

Results indicated that if all the riders wore surgical masks, the dose can be reduced by 50%. This study assumed an index patient would cough once when the patient entered the elevator. The cough would cause other riders inhaling approximately 6 orders of magnitude higher particle mass than continuous breath by the index patient for the whole duration of the ride.

Different scenarios for people wearing surgical mask

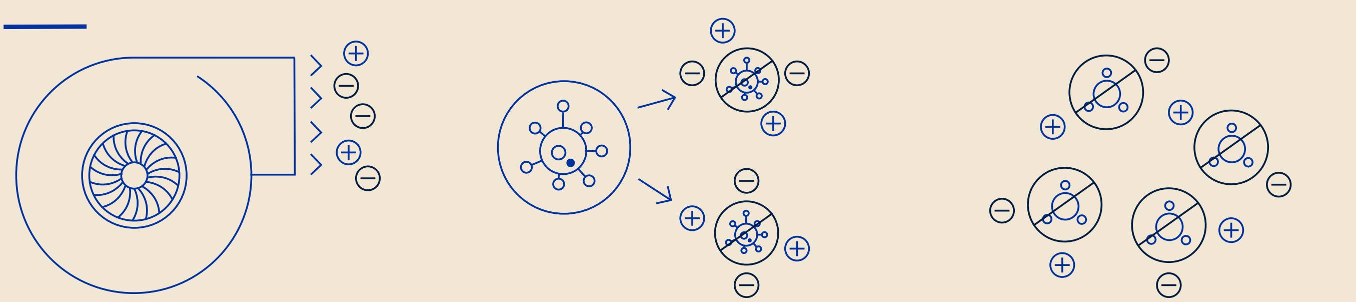
Different scenarios	Index person A	Other people B, C, D, E, F
Scenario 1	No mask	No mask
Scenario 2	Surgical mask	No mask
Scenario 3	No mask	Surgical mask
Scenario 4	Surgical mask	Surgical mask

Accumulated doses for different scenarios of wearing mask

Filtration efficiency	Other people B, C, D, E, F
Scenario 1	0.0%
Scenario 2	33.3%
Scenario 3	33.3%
Scenario 4	55.5%

We also examined the impact of needlepoint bipolar ionization as a cab air purification method. Bipolar ionization is a technology used to improve air quality and lower the intensity of exposure that has years of research and test results supporting its safety and efficacy. Bipolar ionization emits both positively and negatively charged particles that attach to and deactivate harmful substances like bacteria, allergens, mold, viruses, volatile organic compounds (VOCs) and other particulates (Essien, 2017 and Hagbom, 2015).

HOW IT WORKS

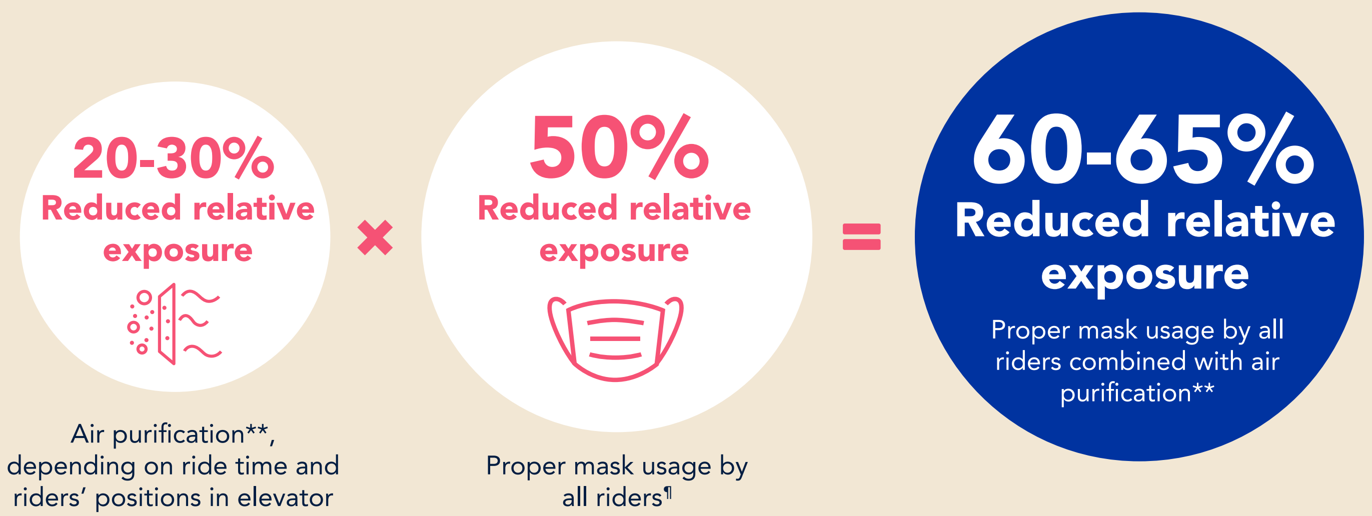


1. Ionizers generate and disperse both negative and positive ions.
2. As bacteria, viruses or other cells divide, the ions attach to the cells, causing a chemical reaction.
3. These harmful viruses or other pathogens are neutralized – reducing the potential spread of airborne particles.

For more details on needlepoint bipolar ionization and other air purification solutions, see our "Air purification in elevators today" technical brief – available at otis.com

In the case of bacteria and viruses, this chemical reaction both depletes their ability to function, by causing oxidative stresses within the organism, and causes physical destruction of their outer layer, effectively inactivating them. Particulate matter can be removed as air ions attach to them, causing them to become ionized and in turn attract other charged particles, increasing the rate of settling via gravity (Kim, 2017).

Our modeling indicated that the use of NPBI reduced risk exposure 20 to 30%, depending on the ride time and riders' positions within the elevator. Furthermore, the use of NPBI combined with proper mask usage by all passengers yielded a 60 to 65% reduction in relative risk.



** Needlepoint bipoloar ionization (NPBI) as compared with no air purification device. Additional details on the study can be found at otis.com.

¶ Proper mask usage compared with no masks. Assumes proper mask wearing of typical cloth or surgical style mask per WHO and CDC guidelines.

Key conclusions

This investigation used a combined CFD and multizone model to study airborne particle transmission of COVID-19 in taking an elevator in a typical office building with 35 floors. The CFD simulated the dispersion of the airborne particles exhaled out by an index patient through breathing in the elevator ride. The multizone model was used to calculate airflow between floors and hoistway and airflow in and out of the elevator through cracks and small openings. The study calculated the accumulated dose of susceptible riders in taking elevators with the index patient under different conditions, such as different ventilation rate, air supply method, elevator cab geometry and intervention method.

Purification solutions reduce exposure **by an additional 20 to 30%**

Proper mask usage by all riders combined with NPBI **can reduce relative exposure 60-65%**

Elevators have a **high level of air exchange, lowering exposure levels**

Travel in an elevator poses **no greater risk of exposure than a short time spent in an office or on a bus**

Proper mask usage **reduces exposure by 50%**

The intervention methods studied were wearing surgical masks by the riders and using NPBI technology in the elevator. This investigation also studied a case with a single cough from the index patient when the patient entered the elevator. For comparison, we also calculated accumulated dose for occupants staying eight hours in a typical office with 5 ACH clean air supply and a one-hour ride in a bus with 10 ACH clean air supply and 10 ACH air supply with 90% recirculated air. The study led to the following conclusions:

- Due to the short duration of the elevator ride, elevators with high ventilation had low risk. For the reference case with a 350 cfm ventilation rate, the highest accumulated particle dose by a susceptible person close to the index patient was 1.59.
- Because of the highly nonuniform distribution of the particles in the elevator cab, the accumulated dose was not inversely proportional with the ventilation rate. Dose was impacted by passenger position relative to the index patient. We also found that a deep cab could trap the particles inside the elevator, and air supply direction had an impact on the particle dispersion in the elevator cab.

- The dose in a well-ventilated elevator with 350 cfm flow was equivalent to a four-minute stay in the office with 5 ACH clean air supply. Even for a poorly ventilated elevator with 55 cfm flow, the dose for the ride was the same as a 15-minute stay in the office. The bus with 10 ACH outside air was very clean, but the bus with 90% of recirculated air was 25 times dirtier than the elevator.
- Intervention methods can further reduce exposure. For example, by using bipolar ionization, exposure can be reduced further by 20 to 30% depending on the ride time and passenger position.
- If all the riders wore surgical masks, the dose can be reduced by 50%. This study assumed an index patient would cough once when the patient entered the elevator. The cough would cause other riders inhaling approximately 6 orders of magnitude higher particle mass than continuous breath by the index patient for the whole duration of the ride.
- The use of NPBI combined with proper mask usage by all passengers can further reduce exposure by 60-65%.

LIMITATIONS

This investigation had the following limitations:

- Since the numerical simulation of the entire process was very difficult, this study separated the whole process into eight sub-cases and transferred data after each sub-case simulation. Since the mesh for each case could not be exactly the same, therefore, some errors may have been introduced.
- Since we need to simulate walking people, using a real-shaped person would demand tremendous computing resources. In addition, Nielson (2003) found that there was no big difference in heat transfer and flow between a real-shaped person and simplified person. Therefore, this study used a rectangular column to simulate a person.
- We assumed the HVAC systems in the lobby of floor 1 supplied fresh air in the ceiling, and the lobby was connected with other spaces. Therefore, the outlets were assigned at the two connection walls. For the particular case we simulated, all the particles from the index patient moved upward and then to other spaces. The exposure of all other susceptible riders was almost zero. This may not always be true in reality, while the waiting time of 30 seconds was relatively long. One should not neglect the impact of exposure on the susceptible riders.
- This study used a computer cluster to conduct the CFD simulations. Each simulation used two nodes with 24 processor cores per node on Skylake CPUs @ 2.60GHz. The memory per node was 96 GB. The average computing time for each sub-case was almost 12 hours. That means each test case with eight sub-cases needed almost 100 hours of computing time. The computational effort was significant.

FURTHER AREAS OF STUDY

The project was a first phase of the elevator study initiated by Otis. After more than a three-month investigation by two full-time postdocs, this project has achieved the initial objectives. However, the research team and the ad hoc review committee recommended the following areas for further study in the near future.

- Validation for the simulation results is essential. However, due to the short duration of this project, we conducted only numerical simulations for the particle distributions based on our previous experience. Experimental validation of the numerical results should be conducted.
- This investigation considered two intervention methods: NPBI disinfection and wearing masks. Other methods such as photocatalytic oxidation, ultraviolet disinfection, HEPA filtering, etc. should be examined.
- This study considered only the breathing and coughing scenario. However, the geometric diameter, size and number of particles generated by breathing, coughing, talking and sneezing are different. The mass of large particles due to talking, coughing and sneezing could be several orders of magnitude higher than that of breathing. It is important to improve the reference case design so that the accumulated mass doses can be determined. By working with epidemiologists and toxicologists, it would be possible to determine a more definitive infection risk probability.
- This project focused mainly on airborne particles, which the WHO, CDC and other experts have identified to be a more likely cause of infection risk. There are, however, other means of potential transmission that we did not model in this study. For instance, since elevator spaces are very small, large droplets could be spread to the breathing zone via direct contact or projection of droplets due to momentum. This should be further studied.
- It is essential to consider the impact of different social distancing, especially facing position of the riders with different loading capacity. The study has found the importance of the positions between normal and deep cabs.
- In addition, fomite contact should not be overlooked on elevators. Our simulations can determine particle deposition on different surfaces, such as the number keyboard and handrails in an elevator. We should study if particle deposition would be a concern for infection transmission by fomite contacts.
- Our study has assumed that the elevator cab would come with clean conditions. For frequently used elevators, the cab may contain the COVID-19 virus. It would be beneficial to study if cabs should be disinfected before the next service and how long it takes to vent the cab to acceptable conditions.
- The current study used standard door closing/opening times. Air exchange when doors open, including the length of time doors are open, should be further studied. The study may include the impact of small pressure differences between cab and landing area versus passenger drag. It could also examine whether it is better to do a straight shot to destination (less time) or to stop periodically and have more ventilation when there is an infected person on board.

Made to move you™

This study and its findings are just a part of our commitment to providing elevator passengers with science-based information to help them make informed decisions about elevators throughout the COVID-19 pandemic and into the future. Otis has supported customers from the outset of the pandemic with resources and behavioral guidance as well as new solutions and technologies. We will continue to innovate and drive research that helps safely move the world forward.

Visit otis.com to request the full technical paper and view other resources related to the study, along with solutions and strategies for enhancing passenger safety.

About the team

The research was led by Dr. Qingyan (Yan) Chen of Purdue University, along with two postdoctoral candidates. The team worked closely with technical experts at Otis to facilitate the study, achieve all of the outlined objectives and clearly communicate the findings.

Qingyan (Yan) Chen, Ph.D. is the James G. Dwyer Professor of Mechanical Engineering at Purdue University and the Editor-in-Chief of Building and Environment. He is widely recognized for his research into the spread of infectious disease through indoor air systems – and how to prevent it.

Chen earned his Bachelor of Engineering degree in 1983 from Tsinghua University, China, and a Master of Engineering degree in 1985 and Ph.D. in 1988 from the Delft University of Technology (TU Delft) in the Netherlands. He conducted his postdoctoral research as a research scientist at the Swiss Federal Institute of Technology (ETH-Zurich) and worked as a project manager for TNO in the Netherlands. Before he joined Purdue University, he was a faculty member at TU Delft and the Massachusetts Institute of Technology (MIT). Chen has parallel appointments at universities in Australia, Europe and China.

Chen's current research topics include indoor environment, aircraft cabin environment and energy-efficient, healthy and sustainable building design and analysis. He has published three books and over 470 journal and conference papers, and has been invited to deliver more than 170 lectures internationally.

In recent years, Chen has received several technical paper and poster awards and Distinguished and Exceptional Service Awards from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). He is also a fellow of ASHRAE and the International Society of Indoor Air Quality. Before he became the Editor-in-Chief of Building and Environment, he served as an associate editor of HVAC&R Research and was a member of the editorial boards of six other journals.

Sumei Liu, Ph.D. is a postdoctoral researcher at Tianjin University, China. Her Ph.D. thesis developed advanced models for accurate simulation of airflow in a building community. She received her Bachelor of Science degree from Hunan University, China, and worked as a consulting engineer at Built Environment Group in Tianjin, China, before pursuing her Ph.D. degree at Tianjin University. She spent time at Purdue University as a visiting scholar and postdoctoral researcher.

Xingwang Zhao, Ph.D. received his Bachelor of Science degree from Chongqing University, China, and a Ph.D. from Tianjin University. He was a visiting scholar and postdoctoral researcher at Purdue University before joining Southeast University, China, for his second postdoc position. His past research included study and design of indoor thermal and air quality environments using the adjoint method – an optimization method to search for boundary conditions according to the indoor environment design objective.

Stephen R. Nichols is a systems engineer with interests in product development, architecture, innovation and strategy. Nichols is interested in finding simplicity in complex systems as well as the intersection of human experiences and people-centered design with vertical transportation technology, building ecosystems and urban environments. He is based at Otis' engineering center and world headquarters in Farmington, Connecticut. He is a two-time National Academy of Engineering Frontiers of Engineering alumni and received the 2019 Gilbreth lectureship. He has earned degrees in mechanical engineering from Tufts University and Rensselaer Polytechnic Institute (RPI) and a professional certificate in systems engineering from MIT. Since March 2020 he has been the research, development and integration lead on the cross-functional global task force at Otis focused on pandemic response, including leading customer-facing rapid innovation, technology and product development, research, strategy and partnership efforts.

James T. Auxier, Ph.D. leads global technology development at Otis focused on emerging technology trends, business needs and strategic areas of technology development. He has previous experience in the building systems, aerospace and medical device industries and extensive university partnership and research experience, including 15 years focused on aerothermal technology development. He has earned degrees in biomedical engineering from Yale University, a master's in mechanical engineering from Stanford University and his Ph.D. in biomedical engineering from the University of Kentucky.

Tricia Derwinski has more than 30 years of Otis experience in the development of systems, subsystems and components. Her areas of emphasis include the design, integration and development of cab shells and structural ceilings, and forced and natural ventilation. She was lead engineer for the modernization of the Empire State Building's elevators, as well as the systems lead for numerous iconic buildings and major projects across the globe. She has a Bachelor of Science degree in civil engineering from Washington University and a Master of Science degree in mechanical engineering from the University of Connecticut. She is a longtime member of both the National Elevator Industry, Inc. (NEII) Performance Standards Committee and the American Society of Mechanical Engineers (ASME) A17 International Standards Committee, as well as a participant in several ISO efforts related to lift and escalator ride quality.

Murilo Bonilha, Ph.D. is the Director, System Architecture, Innovation and Modeling at Otis. Prior to joining Otis in December 2019, Bonilha worked at United Technologies Corporation (UTC), where he had a diverse career, including engineering management, physics-based modeling and other roles, including international leadership assignments in Shanghai, China, and Cork, Ireland. Bonilha holds a Ph.D. in acoustics and vibration from the University of Southampton, England; a Master of Science in systems architecture and engineering from the University of Southern California in Los Angeles; a Master of Science in mechanical engineering from Federal University of Santa Catarina, Brazil; and a Bachelor of Science in naval architecture and marine engineering from University of São Paulo, Brazil.

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Bibliography

Allen J G, Macomber J D. "What Makes an Office Building 'Healthy.'" Harvard Business Review, April 29, 2020. See: https://hbr.org/2020/04/what-makes-an-office-building-healthy

Allen J G. "Research: Stale Office Air Is Making You Less Productive." Harvard Business Review, March 21, 2017. See https://hbr.org/2017/03/research-stale-office-air-is-making-you-less-productive

American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Handbook - HVAC Applications (SI). Atlanta, Georgia, USA. 2007.

American Society of Heating, Refrigerating and Air-Conditioning Engineers Position Document on Filtration and Air Cleaning reaffirmed by Technology Council on January 13, 2018, after initial publication on January 29, 2015. See: https://www.ashrae.org/file%20library/about/position%20documents/filtration-and-air-cleaning-pd.pdf

American Society of Mechanical Engineers. A17.1/CSA B44 Handbook on Safety Code for Elevators and Escalators.

Axley J. "Multizone Airflow Modeling in Buildings: History and Theory." HVAC&R Research, 13:907-928. 2007.

Bae S, Shin H, Koo H, Lee S, Yang J, Yon D. "Asymptomatic Transmission of SARS-CoV-2 on Evacuation Flight." Emerging Infectious Diseases, 26(11):2705-2708. 2020.

Blocken B. 2020. https://www.youtube.com/watch?v=MvLYHSODHVo

Bolster D T, Linden P F. "Particle Transport in Low-Energy Ventilation Systems: Part 2: Transients and Experiments." Indoor Air, 19:130-144. 2009.

Buonanno G, Stabile L, Morawska L. "Estimation of Airborne Viral Emission: Quanta Emission Rate of SARS-CoV-2 for Infection Risk Assessment." Environment International, 141. 2020.

Centers for Disease Control and Prevention. 2019. https://www.cdc.gov/coronavirus/2019-ncov/faq.html#Spread.

Centers for Disease Control and Prevention DC/National Institute for Occupational Safety and Health. "Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings." Publication No. 2009-105. 2009.

Chao C Y H, Wan M P. "A Study of the Dispersion of Expiratory Aerosols in Unidirectional Downward and Ceiling-Return Type Airflows Using a Multiphase Approach." Indoor Air, 16:296-312. 2006.

Chao C Y H, Wan M P, Morawska L, Johnson G R, Ristovski Z D, Hargreaves M, Mengersen K, Corbett S, Li Y, Xie X, Katoshevski D. "Characterization of Expiration Air Jets and Particle Size Distributions Immediately at the Mouth Opening." Journal of Aerosol Science, 40(2):122-133. 2009.

Chen C, Lin C H, Jiang Z, Chen Q. "Simplified Models for Exhaled Airflow From a Cough With the Mouth Covered." Indoor Air, 24(6):580-591. 2014.

Chen C, Zhao B, Cui W, Dong L, An N, Ouyang X. "The Effectiveness of an Air Cleaner in Controlling Particle/Aerosol Particle Dispersion Emitted From a Patient's Mouth in the Indoor Environment of Dental Clinics." Journal of the Royal Society Interface, 7:1105-1118. 2010.

Chen C, Zhao B, Yang X, Li Y. "Role of Two-Way Airflow Owing to Temperature Difference in Severe Acute Respiratory Syndrome Transmission: Revisiting the Largest Nosocomial Severe Acute Respiratory Syndrome Outbreak in Hong Kong." Journal of the Royal Society Interface, 8:699-710. 2011.

Chen J, He H, Cheng W, Liu Y, Sun Z, Chai C, Kong Q, Sun W, Zhang J, Guo S, Shi X, Wang J, Chen E, Chen Z. "Potential Transmission of SARS-CoV-2 on a Flight From Singapore to Hangzhou, China: An Epidemiological Investigation." Travel Medicine and Infectious Disease, 36:101816. 2020.

Chen Q. "Ventilation Performance Prediction for Buildings: A Method Overview and Recent Applications." Building and Environment, 44:848-858. 2009.

Chen Q, Zhao S L, Liu S. "Evaluation of COVID-19 Infection Risk When Taking Elevators." Otis Elevator Company. December 2020.

Cheng V C, Wong S C, Chuang V W, So S Y, Chen J H, Sridhar S, To K K, Chan J F, Hung I F, Ho P L, Yuen K Y. "The Role of Community-Wide Wearing of Face Mask for Control of Coronavirus Disease 2019 (COVID-19) Epidemic Due To SARS-CoV-2." Journal of Infection. 2020.

Chin A W H, Poon L L M. "Stability of SARS-CoV-2 in Different Environmental Conditions." The Lancet Microbe, 1(1):p. e10. 2020.

Choi E M, Chu D, Cheng P, Tsang D, Peiris M, Bausch D G, Poon L L, Watson-Jones D. "In-Flight Transmission of SARS-CoV-2." Emerging Infectious Diseases, 26(11):2713-2716. 2020.

Choudhury D. "Introduction to the Renormalization Group Method and Turbulence Modeling." Canonsburg, Fluent Inc. Technical Memorandum TM-107. 1993.

Dai H, Zhao B. "Association of Infected Probability of COVID-19 With Ventilation Rates in Confined Spaces: A Wells-Riley Equation Based Investigation." 2020.

Darnell M E, Subbarao K, Feinstone S M, Taylor D R. "Inactivation of the Coronavirus That Induces Severe Acute Respiratory Syndrome SARS-CoV." Journal of Virology, Methods 121, 85-91. 2004.

Defile N C, Allen J G, Scheepers P, Levy J. "The COVID-19 Pandemic: A Moment for Exposure Science." Journal of Exposure Science & Environmental Epidemiology, April 29, 2020. See: https://www.nature.com/articles/s41370-020-0225-3

Derwinski T. "Safety Chain: A Look at Safety Systems in a Modern High-Rise Elevator in Light of 2018 Chicago Incident." Elevator World, June 2019. See: www.elevatorworld.com

FUJITEC company. 2008. http://www.fujitec.com.ar/english/IHO_ionful.html.

GAMBIT CFD Preprocessor. User's Guide. Lebanon, NH: Fluent Inc. 1998.

Gao N, Niu J. "Modeling Particle Dispersion and Deposition in Indoor Environments." Atmospheric Environment, 41:3862-3876. 2007.

Gao X, Li Y, Xu P, Cowling B J. "Evaluation of Intervention Strategies in Schools Including Ventilation for Influenza Transmission Control." Building Simulation, 5:29-37. 2012.

Gupta J K, Lin C H, Chen Q. "Characterizing Exhaled Airflow From Breathing and Talking." Indoor Air, 20:31-39. 2010.

Gupta J K, Lin C H, Chen Q. "Transport of Expiratory Particles in an Aircraft Cabin." Indoor Air, 21:3-11. 2011.

Hang J, Li Y, Jin R. "The Influence of Human Walking on the Flow and Airborne Transmission in a Six-Bed Isolation Room: Tracer Gas Simulation." Building and Environment, 77:119-134. 2014.

Hagbom M, Nordgren J, Nybom R, Hedlund K O, Wigzell H, Svensson L. "Ionizing Air Affects Influenza Virus Infectivity and Prevents Airborne-Transmission." Scientific Reports, 5:11431. 2015.

Hoehl S, Karaca O, Kohmer N, Westhaus S, Graf J, Goetsch U, Ciesek S. "Assessment of SARS-CoV-2 Transmission on an International Flight and Among a Tourist Group." Journal of the American Medical Association, JAMA Network Open, 3(8):e2018044. 2020.

Hyun J, Lee S G, Hwang J. "Application of Corona Discharge-Generated Air Ions for Filtration of Aerosolized Virus and Inactivation of Filtered Virus." Journal of Aerosol Science. 2017.

iF World Design Guide. https://ifworlddesignguide.com/entry/76697-mive

Jones R M, Masago Y, Bartrand T, Nicas M, Rose J B. "Characterizing the Risk of Infection From Mycobacterium Tuberculosis in Commercial Passenger Aircraft Using Quantitative Microbial Risk Assessment." Risk Analysis, 29:355-365. 2009.

Khanh N C, Thai P Q, Quach H L, Thi N A H, Dinh P C, Duong T N, Mai L T Q, Nghia N D, Tu T A, Quang L N, Quang T D, Nguyen T T, Vogt F, Anh D D. "Transmission of SARS-CoV-2 During Long-Haul Flight." Emerging Infectious Diseases, 26(11):2617-2624. 2020.

Ko G, Thompson K M, Nardell E A. "Estimation of Tuberculosis Risk on a Commercial Airliner." Risk Analysis, 24:379-88. 2004.

Kratzel A, Todt D, V'kovski P, Steiner S, Gultom M L, Thao T T N, Ebert N, Holwerda M, Steinmann J, Niemeyer D, Dijkman R, Kampf G, Drosten C, Steinmann E, Thiel V, Pfaender S. "Efficient Inactivation of SARS-CoV-2 by WHO-Recommended Hand Rub Formulations and Alcohols." bioRxiv. 2020.

Kujundzic E, Hernandez M, Miller S L. "Ultraviolet Germicidal Irradiation Inactivation of Airborne Fungal Spores and Bacteria in Upper-Room Air and HVAC In-Duct Configurations." Journal of Environmental Engineering Science, 6:1-9. 2007.

Launder B E, Spalding D B. "The Numerical Computation of Turbulent Flows." Computer Methods in Applied Mechanics and Energy, 3:269-289. 1974.

Li X, Niu J, Gao N. "Spatial Distribution of Human Respiratory Particle Residuals and Exposure Risk for the Co-Occupant Under Different Ventilation Methods." HVAC&R Research, 17:432-445. 2011.

Li X, Niu J, Gao N. "Co-Occupant's Exposure of Expiratory Particles — Effects of Mouth Coverings." HVAC&R Research, 18:575-587. 2013.

Li Y, Qian H, Hang J, Chen X, Hong L, Liang P, Li J, Xiao S, Wei J, Liu L, Kang M. "Evidence for Probable Aerosol Transmission of SARS-CoV-2 in a Poorly Ventilated Restaurant." medRxiv, 04.16.20067728. 2020.

Liu X, Wu J, Liu M, Dai Y, Zhou D, Li W, Lv P, Zhou N, Wu P. "Presymptomatic Transmission of COVID-19 in a Cluster of Cases Occurred in Confined Space: A Case Report." 2020.

Lim T, Cho J, Kim B S. "Predictions and Measurements of the Stack Effect on Indoor Airborne Virus Transmission in a High-Rise Hospital Building." Building and Environment, 46:2413-2424. 2011.

Lopez G, Northrop A. "How To Weigh the Risk of Going Out in the Coronavirus Pandemic, in One Chart." Vox. July 3, 2020. https://www.vox.com/2020/5/22/21266756/coronavirus-pandemic-covid-risks-social-distancing-chart

Mandavilli A. "239 Experts With One Big Claim: The Coronavirus Is Airborne." The New York Times, July 4, 2020. See: https://www.nytimes.com/2020/07/04/health/239-experts-with-one-big-claim-the-coronavirus-is-airborne.html

Marr L, Corsi R. "SARS-CoV-2 in Indoor Air: Principles and Scenarios." Indoor Air Quality Science and Technology webinar presented by the United States Environmental Protection Agency, July 16, 2020. See: https://www.epa.gov/indoor-air-quality-iaq/indoor-air-quality-science-and-technology

Mazumdar S, Poussou S, Lin C H, Isukapalli S S, Plesniak M W, Chen Q. "The Impact of Scaling and Body Movement on Contaminant Transport in Airliner Cabins." Atmospheric Environment, 45(33):6019-6028. 2011.

Mazumdar S, Chen Q. 2009. "A One-Dimensional Analytical Model for Airborne Contaminant Transport in Airliner Cabins." Indoor Air, 19(1):3-13. 2009.

Mazumdar S, Long Z, Chen Q. "A Coupled CFD and Analytical Model to Simulate Airborne Contaminant Transmission in Cabins." Indoor and Built Environment, 23:946-954. 2014.

McDevitt J J, Lai K M, Rudnick S N, Houseman E A, First M W, Milton D K. "Characterization of UVC Light Sensitivity of Vaccinia Virus." Applied and Environmental Microbiology, 73:5760-5766. 2007.

McDevitt J J, Rudnick S N, Radonovich L J. "Aerosol Susceptibility of Influenza Virus to UV-C Light." Applied and Environmental Microbiology, 78:1666-1669. 2012.

McLean R. "The Mechanism of Spread of Asian Influenza: General Discussion." The American Review of Respiratory Disease, 83:36-38. 1961.

Megri A C, Haghighat F. "Zonal Modeling for Simulating Indoor Environment of Buildings: Review, Recent Developments, and Applications." HVAC&R Research, 13:887-905. 2007.

Mitchell B W, King D J. "Effect of Negative Air Ionization on Airborne Transmission of Newcastle Disease Virus[J]." Avian Diseases, 38(4):725-732. 1994.

Morawska L, Tang J W, Bahnfleth W, Bluyssen P M, Boerstra A, Buonanno G, Cao J, Dancer S, Floto A, Franchimon F, Haworth C, Hogeling J, Isaxon C, Jimenez J L, Kurnitski J, Li Y, Loomans M, Marks J, Marr L C, Mazzarella L, Melikov A K, Miller S, Milton K D, Nazaroff W, Nielsen P V, Noakes C, Peccia J, Querol X, Sekhar C, Seppänen O, Tanabe S-I, Tellier R, Tham K K, Wargocki P, Wierzbicka A, Yao M. "How Can Airborne Transmission of COVID-19 Indoors Be Minimised?" Environment International, 142:105832. 2020.

Murakami S, Kato S, Nagano S, Tanaka S. Diffusion Characteristics of Airborne Particles with Gravitational Settling in a Convection-Dominant Indoor Flow Field. ASHRAE Transactions, 98(1):82-97. 1992.

National Academies of Sciences, Engineering and Medicine. "Does Ultraviolet (UV) Light Kill the Coronavirus?" Based on Science, published on April 22, 2020. See: https://www.nationalacademies.org/based-on-science/covid-19-does-ultraviolet-light-kill-the-coronavirus

Nichols S, Auxier J. "Airflow and Elevators: Highlights of an Airflow Study Conducted to Determine the Relative Risk of COVID-19 Transmission Among Elevator Passengers." Otis Elevator Company. January 2021.

Nielsen P V. "Benchmark Test for a Computer Simulated Person." Indoor Air 14.7. 2003:144-156.

Noakes C J, Khan M A I, Gilkeson C A. "Modeling Infection Risk and Energy Use of Upper-Room Ultraviolet Germicidal Irradiation Systems in Multi-Room Environments." Science and Technology for the Built Environment, 21:99-111. 2015.

Poussou S B, Mazumdar S, Plesniak M W, Sojka P E, Chen Q. 2010. "Flow and Contaminant Transport in an Airliner Cabin Induced by a Moving Body: Model Experiments and CFD Prediction." Atmospheric Environment, 44(24):2830-2839.

Public Health Agency of Canada. "Prevention and Control for Health Care Settings: Canadian Pandemic Influenza Preparedness: Planning Guidance for the Health Sector." See: https://www.canada.ca/en/public-health/services/flu-influenza/canadian-pandemic-influenza-preparedness-planning-guidance-health-sector/prevention-and-control-of-influenza-during-a-pandemic-for-all-healthcare-settings.html

Shao S, Zhou D, He R, et al. "Risk Assessment of Airborne Transmission of COVID-19 by Asymptomatic Individuals Under Different Practical Settings." Journal of Aerosol Science, 151:105661. 2021.

Singh N, Kaczmarczyk S, Ehrl T. An Analysis of Airflow Effects in Lift Systems. The 7th Symposium of Lift and Escalator Technologies, Northampton University, UK. 2017.

Speake H, Phillips A, Chong T, Sikazwe C, Levy A, Lang J, Scalley B, Speers D J, Smith D W, Effler P, McEvoy S P. "Flight-Associated Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 Corroborated by Whole-Genome Sequencing." Emerging Infectious Diseases, 26(12):2872-2880. 2020.

Smagorinsky J. "General Circulation Experiments with the Primitive Equations I: The Basic Experiment." Monthly Weather Review, 91:99-164. 1963.

Song D, Lim H. "Application of the Mechanical Ventilation in Elevator Shaft Space to Mitigate Stack Effect Under Operation Stage in High-Rise Buildings." Indoor and Built Environment, 23(1):81-91. 2014.

Song F, Zhao B, Yang X, Jiang Y, Gopal V, Dobbs G, Sahm M. "A New Approach on Zonal Modeling of Indoor Environment with Mechanical Ventilation." Building and Environment, 43:278-286. 2008.

United States Environmental Protection Agency. "Coronavirus Cases Trigger EPA Rapid Response." Released January 29, 2020. See: https://www.epa.gov/pesticides/coronavirus-cases-trigger-epa-rapid-response

Walker C M, Ko G. "Effect of Ultraviolet Germicidal Irradiation on Viral Aerosols." Environmental Science & Technology, 41:5460-5465. 2007.

Walkinshaw D S. "Germs, Flying and the Truth." ASHRAE Journal, 52:70-73. 2010.

Wang J, Chow T T. "Influence of Human Movement on the Transport of Airborne Infectious Particles in Hospital." Journal of Building Performance Simulation, 8(4):205-215. 2015.

Wang L, Dols W S, Chen Q. "Using CFD Capabilities of CONTAM 3.0 for Simulating Airflow and Contaminant Transport In and Around Buildings." HVAC&R Research, 16(6):749-763. 2010.

World Health Organization. Scientific brief: "Transmission of SARS-CoV-2: Implications for Infection Prevention Precautions." July 9, 2020. See: https://www.who.int/publications/i/item/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations

Xie C, Zhao H, Li K, Zhang Z, Lu X, Peng H, Wang D, Chen J, Zhang X, Wu D, Gu Y, Yuan J, Zhang L, Lu, J. "The Evidence of Indirect Transmission of SARS-CoV-2 Reported in Guangzhou, China." BMC Public Health, 20(1):1-9. 2020.

Xu P, Kujundzic E, Peccia J, Schafer M P, Moss G, Hernandez M, Miller S L. "Impact of Environmental Factors on Efficacy of Upper-Room Air Ultraviolet Germicidal Irradiation for Inactivating Airborne Mycobacteria." Environmental Science and Technology, 39(24):9656-9664. 2005.

Xu P, Peccia J, Fabian P, Martyny J W, Fennelly K P, Hernandez M, Miller S L. "Efficacy of Ultraviolet Germicidal Irradiation of Upper-Room Air in Inactivating Airborne Bacterial Spores and Mycobacteria in Full-Scale Studies." Atmospheric Environment, 37:405-419. 2003.

Yakhot V, Orszag SA. "Renormalization Group Analysis of Turbulence." Journal of Scientific Computing, 1:3-51. 1986.

Young L, Wormser G. "The Resurgence of Tuberculosis." Scandinavian Journal of Infectious Diseases, Supplement, 93:9-19.

You R, Lin C H, Wei D, Chen Q. "Evaluating the Commercial Airliner Cabin Environment with Different Air Distribution Systems." Indoor Air, 29(5):840-853. 2019.

Yu L, Peel G K, Cheema F H, Lawrence W S, Bukreyeva N, Jinks C W, Peel J E, Peterson J W, Paessler S, Hourani M, Ren Z. "Catching and Killing of Airborne SARS-CoV-2 to Control Spread of COVID-19 by a Heated Air Disinfection System." Materials Today Physics, 15:100249. 2020.

Zhang L, Li Y. "Dispersion of Coughed Particles in a Fully Occupied High-Speed Rail Cabin." Building and Environment, 47:58-66. 2012.

Zhang R, Li Y, Zhang A L, Wang Y, Molina M J. "Identifying Airborne Transmission as the Dominant Route for the Spread of COVID-19." Proceedings of the National Academy of Sciences. 2020.

Zhang Z, Zhai Z Q, Zhang W, Chen Q. "Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part 2 - Comparison with Experimental Data from Literature." HVAC&R Research, 13:871-886. 2007.

Zhou Y, Shen J. "Experimental and Numerical Study on the Transport of Droplet Aerosols Generated by Occupants in a Fever Clinic." Building and Environment, 187. 2020.

Zemouri C, Awad S F, Volgenant C M C, Crielaard W, Laheij A M G A, de Soet J J. "Modeling of the Transmission of Coronaviruses, Measles Virus, Influenza Virus, Mycobacterium Tuberculosis, and Legionella Pneumophila in Dental Clinics." Journal of Dental Research, (9):002203452094028. 2020.