Engineered Physical Distance Equivalence for a Cough

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Abstract

This paper compares a sophisticated interior flow model for an airplane to a conical plume model for a coughing passenger. The distance on the aircraft at which the cough particle mass is equal to the mass calculated by the conical model is called the engineered physical distance (EPD). The EPD is evaluated as one layer in a multi-layered system of protections to help minimize the risk of disease transmission throughout the air travel journey. The calculations presented show that the passenger sitting next to the cougher has an EPD of greater than 7 feet (or 2 meters). The engineering of the cabin—including the seating geometry, velocity and direction of air flow, and air exchange rate found on a typical commercial airliner—reduces the exposure to cough particle mass for nearby passengers.

Introduction

Among the industries affected by the SARS-CoV-2 pandemic, the air travel industry saw a drop from 2019 passenger levels of nearly 95% in a matter of weeks (1). As segments of the population continued to travel, questions emerged regarding the relative risk of disease transmission in the air travel system and, specifically, the aircraft cabin. The quantitative relationship between physical distance and disease transmission depends on several factors including the mass of transmitted particles from an infectious index person to an inhaling susceptible person; they are susceptible solely due to exposure to transmitted particles via breathing. Without a transmitted mass, no infection is possible.

The results of the work presented herein show: The aircraft Environmental Control System (ECS) causes the mass transmitted from one passenger to the next to be as low as the mass transmitted between individuals at a much greater distance in a still air environment. The mass of transmitted particles can be compared between environments and used to calibrate equivalent distances of separation between the particle emitter (an infectious index person coughing in this case) and the particle receiver (a susceptible nearby person that inhales the particles).

This paper presents a simple conical distribution of particle mass to the breathing zone of nearby people at various distances, with the particles generated by an infectious person's cough. This conical model is a plume model. A similar estimate of mass presented to the breathing zone of a nearby person has been reported previously for the cabin of a commercial aircraft (2). The distance in an aircraft cabin at which the same mass found by the conical model at a particular distance is determined. Matching the mass calculated by the conical model and that on the aircraft allows an equivalent distance to be determined, i.e., the engineered physical distance (EPD).

The spatial distribution of particles in the aircraft cabin and the time required to remove them makes some models more useful than others in understanding which passengers will be presented with significant particle mass in their breathing zone and which will not. Well-mixed models are often used for the determination of exposure to aerosol particles. The spatial character of particle mass exposure on the aircraft and its relationship to the well-mixed concept is also investigated herein.

Conditions in an Aircraft Cabin

The ECS on a typical passenger aircraft generates approximately twenty to thirty air changes per hour (ACH) when calculated for an empty cabin (3). With the volume of the cabin filled with passengers and luggage, the ACH rate is higher. The cabin air typically consists of 50% outside air and 50% recirculated air. The recirculated air is passed through high-efficiency particulate air (HEPA) filters to remove particles, including those carrying viruses, at an efficacy of 99.97% at the most penetrable particle size of 0.3 µm. Directional air flow from ceiling to floor in a circular pattern, with minimal fore/aft flow, limits particle spread in the cabin (Figure 1). The positioning of passengers facing forward (rather than facing each other), and separation by high-back seats that act as a barrier similar to the Plexiglas™ barriers now commonly seen in other environments, further reduces the between-row airflow.

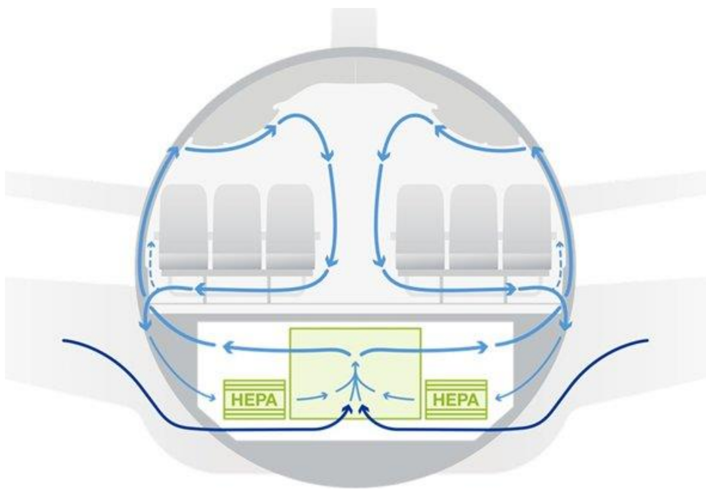

Figure 1. Design for airflow in the passenger cabin.

Methods

Methods needed to compare exposure to expiratory particles from a cough in an aircraft cabin and a conical model are addressed in this section. The mass of particles presented to the breathing zone of nearby persons at various distances was determined by the conical model. Computational fluid dynamics (CFD) simulations were used to determine the mass of particles presented to the breathing zone on the aircraft (2). The particles were tracked over time (i.e., the 4 minutes of the CFD model). The masses presented to the breathing zone via the conical model were compared to the masses presented to the breathing zone of passengers on the aircraft. The ratio of the physical distance in the conical model to the engineered physical distance on the aircraft was calculated.

The Cough

In each simulation, a single cough was emitted by an index person over the course of 0.4 seconds, using a time-dependent flow rate (4) and a particle size distribution that included sizes down to 0.1 µm (5). Cough particles were simulated with the density of water, a volatile fraction of 90% (6), and evaporated to droplet nuclei over approximately 2 seconds using a vapor pressure corrected for the effect of lung surfactants (7). The rates of evaporation in the aircraft vs. in the conical model are different as the latter does not consider evaporation. For the aircraft CFD model, when particles impacted on surfaces, they were captured and removed from the airborne part of the simulation as accreted material. For the conical model, no surface capture was assumed, but the particles above 10 µm in diameter (accounting for 53% of the total mass of the cough particles) were removed in the approximation as having settled under the force of gravity.

The Breathing Zone

For both the aircraft CFD and the conical model, each person's breathing zone, Figure 2, was defined as a cube with side length of 1 ft. and a volume of 0.8 $ft.^3$ after subtracting the volume occupied by the subject's body.

For the aircraft CFD model, the mass of particles in the passenger's breathing zone was tracked throughout the simulation and integrated over the complete 4-minute run-time for each simulation. In previous studies, it was demonstrated that the mass in the breathing zone after a cough in the cabin decays rapidly, i.e., 95% of the cumulative nonvolatile mass was removed in 1.4 minutes (80% in 0.7 min, 99% in 2.3 min) (2).

For the conical model, the cone defined the dilution of the particles, and the mass in the breathing zone was a constant value. No air circulation was assumed for the conical model. Only the conical expansion of the cough particles was used to dilute the particles in the breathing zone. This simplification is reasonable because for the period of a cough and its conical expansion, the effect of airflow in relatively still air environments can be neglected.

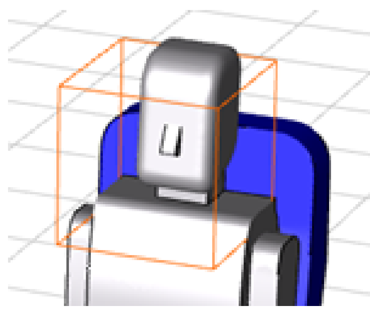

Figure 2. Breathing zone (orange) for a seated subject in the aircraft simulations.

Conical Model

The cone-shaped expansion model was used to determine the number of particles presented to the breathing zone of another individual in still air. The index and the susceptible individuals were placed at various distances apart and facing each other, as shown in Figure 3. Particles larger than 10 µm in diameter were assumed to settle under the force of gravity before reaching the susceptible subject.

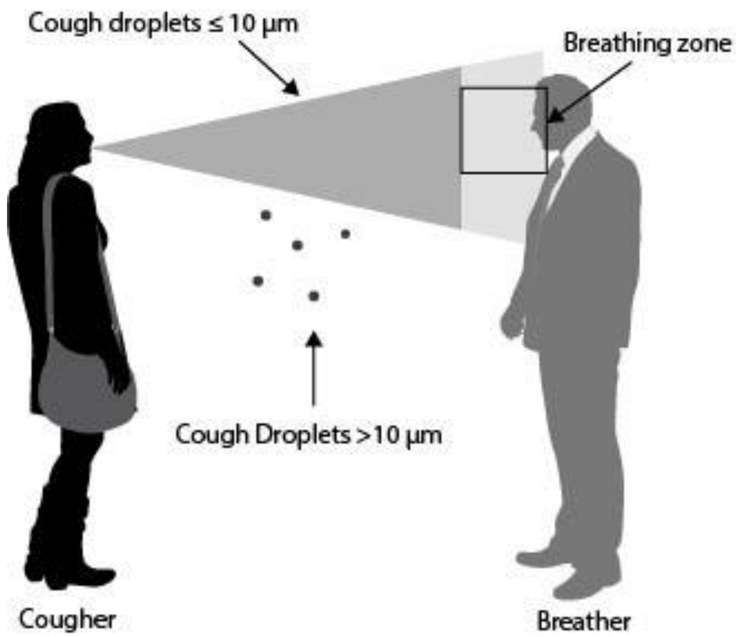

Figure 3. Cough trajectory in the conical model. The black box indicates the breathing zone. The light grey conical section indicates the diluted concentration after conical expansion.

Other assumptions were that the cough follows a conical path, all particles smaller than 10 µm in diameter at the time of emission are able to follow that path the entire length of the cone, particle concentration is uniform within the dilution volume (light grey conical section in Figure 3), and the air exchange rate in the nearby area is zero. With these assumptions, the volume of a circular truncated cone was used to represent the dilution volume:

$$V_{dilution} = \frac{1}{3}\pi\,(r_1^2 + r_1 r_2 + r_2^2)\,h_{bz} \tag{1}$$

$$r_1 = h_{cone}\ \tan\theta \tag{2}$$

$$r_2 = (h_{cone} - h_{bz})\ \tan\theta \tag{3}$$

where h_{bz} is the length of the breathing zone, h_{cone} is the distance between the coughing index and the susceptible subjects, and θ is the angle of the cone. The length of the breathing zone was set to one foot, and the angle of the cone used was 15.5 degrees, assuming a constant cone angle (8). The distance between the index and the susceptible subjects was varied to generate a mass vs. distance dataset.

From the dilution volume, $V_{dilution}$, the fraction of the cough that reaches the breathing zone (x_{bz}) was calculated by assuming a constant concentration within the dilution volume as follows:

$$x_{bz} = \frac{V_{bz}}{V_{dilution}} \tag{4}$$

where the volume of the breathing zone, V_{bz}, was 0.8 ft^3.

The mass of particles that reaches the breathing zone was then calculated from the fraction of cough particles smaller than 10 µm that reaches the breathing zone as follows:

$$m_{bz} = x_{bz} * m_{particles<10\ \mu m} \tag{6}$$

where the mass of particles with a diameter less than 10 µm, $m_{particle<10\mu m}$, was 25.8 µg.

This calculation is a significant simplification of cough dynamics. Particles with an initial diameter of less than 10 µm (47% of the cough's mass) may stop following the simple cone trajectory by slowing down or spreading out due to turbulence. Or the buoyancy of small particles may begin to move them upwards, deviating from the conical path as the larger droplets fall under sedimentation (9); this effect was not considered in this estimate. The various assumptions may or may not result in an overestimation of mass that reaches the breathing zone. However, to account for variation, the mass that reaches the breathing zone was assumed to be one half of the mass calculated from Equations 1 through 5 to ensure an even more conservative approach in later comparisons.

Aircraft CFD Simulations

CFD simulations and analyses were performed using the method described earlier by Davis (2020) (2). Briefly, CFD simulations were performed using Ansys Fluent™ 19.2 computational fluid dynamics simulation software for the aircraft (737 Boeing Sky Interior cabin). Between 10 and 20k computer cores with approximately 800 Ansys Fluent™ licenses were used to perform the CFD analyses. The range of thermal boundary conditions used for the all CFD simulations in the Davis et al. (2020) paper are presented in Table 1.

Table 1. Airflow and thermal boundary conditions used for CFD simulations.

	Airplane
Supply flow rate [Actual ft^3/min]	323 – 588
Return flow rate [Actual ft^3/min]	Same as supply
Air changes per hour	24.7 – 44.9
Relative humidity [%]	0-20
Occupant heat generation [W]	70/person
Walls [°F]	55 – 65
Ceiling, floor, stowage bins	Adiabatic
Front and back interfaces	Periodic
Supply air temperature [°F]	62 – 67
Environment average temperature [°F]	75 – 77

A five-row section of the 737 Boeing Sky Interior (BSI) cabin was used for aircraft simulations, with the seat chart shown in Figure 4.

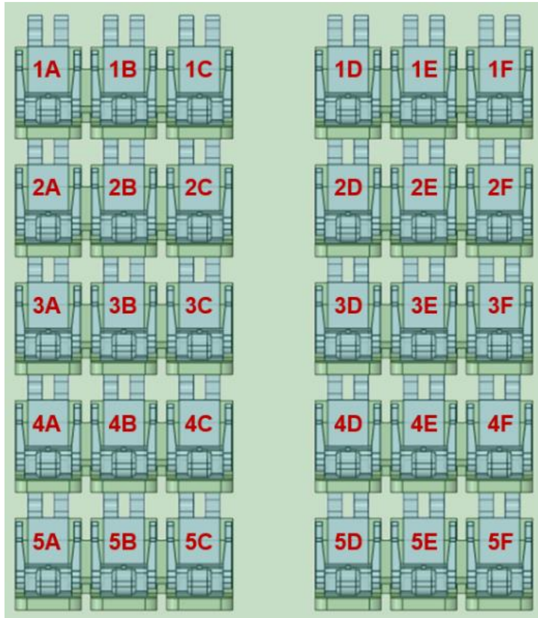

Figure 4. Seat map for airplane cabin simulations.

The cases listed in Table 2 were used for comparison to the conical model. To account for the effects of random low frequency fluctuations in airflow as described earlier (2), initial condition starting times (*Table 2*, Initial Conditions) were analyzed for one of the index positions upon a cough event while holding all other variables constant. This allowed an estimate of variation due to small changes in airflow which are normal in the cabin. These variations did not change the time required for cough particles to be 99% removed. In this study, the Personal Air Outlets (PAOs) common on most commercial aircraft were all in the closed position as analyses of the PAO effects did not yield a clear recommendation for their use.

*Table 2. Case summary for airplane cabin simulations. See reference (**Error! Bookmark not defined.**) for complete description.*

Index Seat	Initial Condition	Flow Rate	Flow Rate (ACFM)
3D	No offset	1	588
3D	90 seconds offset	1	588
3D	120 seconds offset	1	588
3E	No offset	1	588
3F	No offset	1	588
3D	No offset	0.77	453
3D	No offset	0.55	323

Results and Discussion

In this section, the integrated mass in the breathing zone is presented both as a function of seat position and distance from the index passenger, and is also used to investigate the well-mixed assumption. Using the mass presented to the breathing zone in both the conical model and the CFD aircraft model, the engineered physical distance is presented.

Mass Presented in the Breathing Zone

CFD modeling was used to calculate the cough particle mass (in µg) delivered to the breathing zone (0.8 ft^3) directly in front of an aircraft passenger's head. The values presented for a single cough in the aircraft cabin are shown in Figure 5. The position of the coughing index passenger is listed in the header of each plot shown in Figure 5 and excluded from the seat numbers in the plots.

The data demonstrates dependence of the cough particle mass delivered to a given passenger on that passenger's distance from the cougher. Each row contains two triplets of seats: seats A, B and C comprise the triplet on the left side of the airplane and seats D, E and F comprise the triplet on the right side of the airplane. Both the distance across a row and the distance fore and aft in the cabin contribute to differences in the mass presented in the breathing zone of nearby passengers. The maximum mass presented in the breathing zone of a susceptible passenger is 1.9 µg and is associated with an index passenger in the seat next to the susceptible passenger.

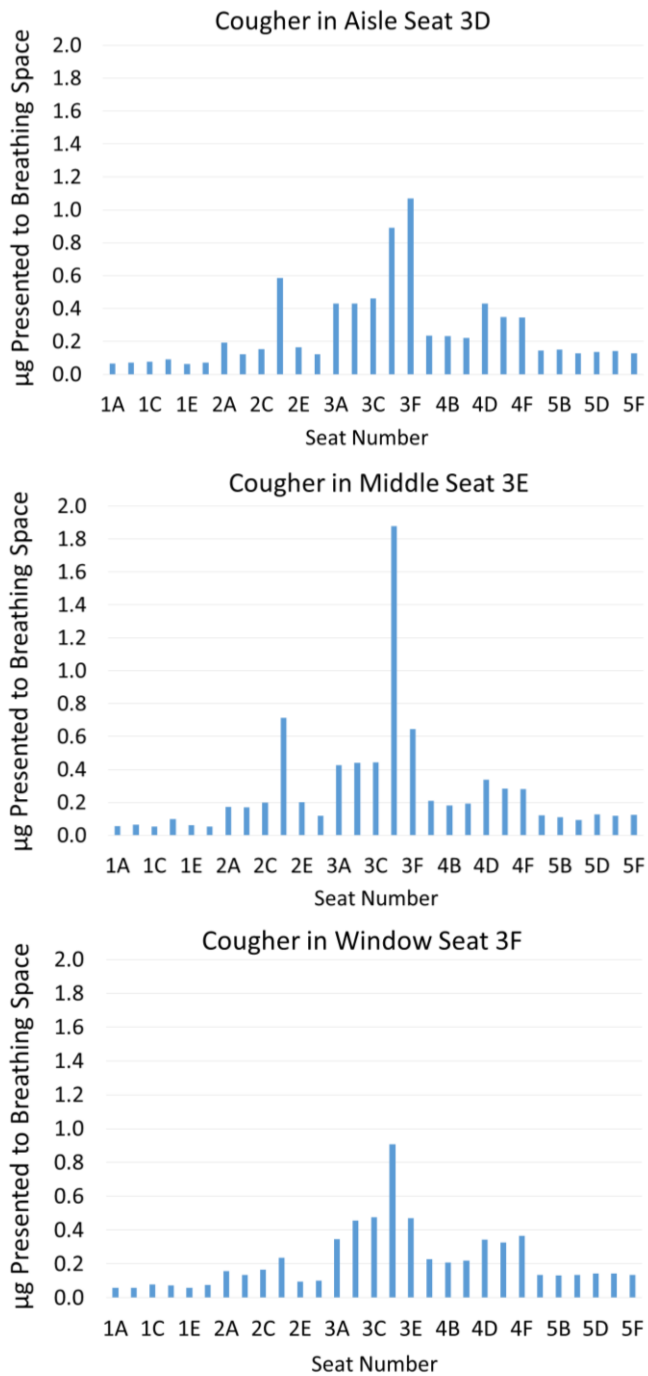

Figure 5. Cough particle mass presented to breathing zone for each seat location, with index location as specified in the header of each plot.

The Well-Mixed Model and Mass Presented in Breathing Zone vs. Distance from Index

The literature is replete with examples of analyses that are reported as pertaining to the aircraft cabin. Many make the error of applying the Wells-Riley well-mixed assumption to the airplane cabin which does not address the direction of flow, or the spatial gradient of concentrations; others fail to acknowledge the decay of particle mass in the breathing zone over time after a perturbation like a cough in the cabin. In comparison, the CFD model presented in this paper* is consistent with empirical studies by Silcott et al. (10). Understanding the effect of distance on the mass presented in the breathing zone is critical to understanding the hypothesis of this paper and the conclusions drawn.

To understand the effect that the aircraft ECS system has on the mass presented in the breathing zone, the distribution of mass around the index passenger should be investigated. One method for investigating the validity of the well-mixed model is to look for decay in the mass as the distance from the index passenger increases; the well-mixed model predicts that such decay should be minimal. Figure 6 (at left) shows the map of the integrated mass in the breathing zone for the single-aisle, thirty-seat 737 aircraft cabin CFD model. The cougher here is seated in seat 3E. At right in Figure 6 the mass is plotted against the distance from the cougher across row 3. The decay in mass away from the cougher is not a perfect fit for any one equation-based model, but is likely a combination of diffusion, advection and convection dispersal. On the time scales important here, processes like diffusion and sedimentation are smaller effects. Complex flow fields (advection) generated by the ECS system account for more of the differences in integrated mass presented in the breathing zone at various distances from the index passenger. The jet velocity of the cough itself is one of the important flow patterns which was accounted for in the CFD model that generated this data. The cough jet and any air movement in the cabin that causes a particle to be accreted on a surface drives down the concentration of particles carried in the flowing air. The positioning of passengers, all facing forward, is one of the protections afforded by the aircraft cabin as it directs the jet of the cough toward the back of the seat in front of the cougher which acts as a barrier.

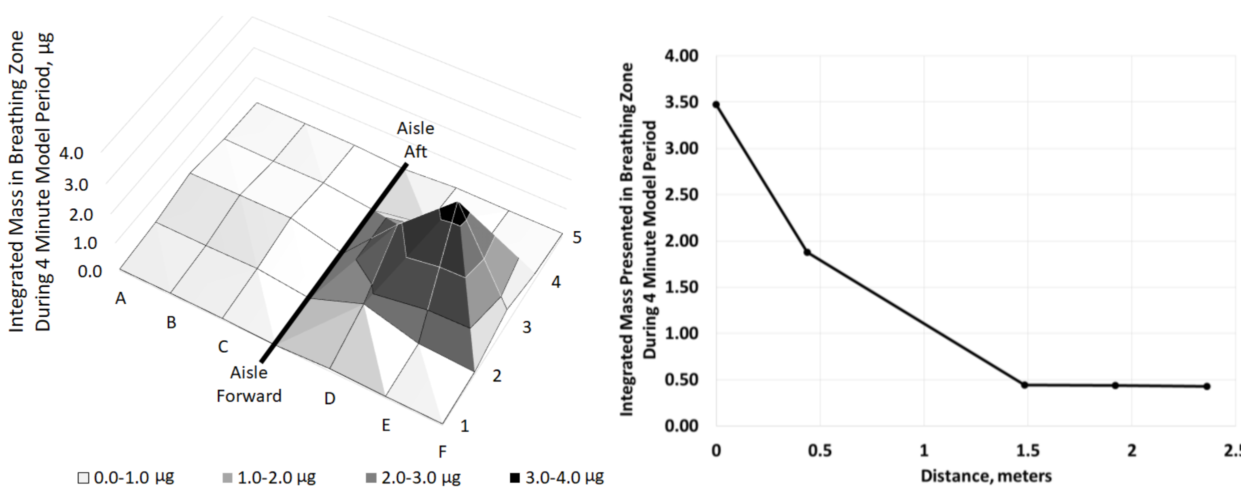

Figure 6. Three-dimensional map of integrated mass in the breathing zone during 4-minute model period reported in micrograms (left), and the same mass vs. distance for a cough (right) across row 3 starting with the cougher in seat 3E.

The CFD modeling method for assigning mass of cough particles presented in the breathing zone of each passenger is a more accurate method than simply applying an instantaneously well-mixed model where

* In earlier work we have demonstrated that the mass in the breathing zone after a cough decays rapidly i.e., 95% of the cumulative nonvolatile mass was removed in 1.4 minutes (80% in 0.7 min, 99% in 2.3 min)

every passenger sees the same mass. The well-mixed model underestimates the mass presented for persons nearby while overestimating the mass presented for those passengers more distant from the cougher.

Based on the data presented in Figure 6 along with studies performed by other teams on aircraft (11), the well-mixed approximation must be rejected for models of the aircraft cabin.

Still Air Conical Model and Airplane CFD Derived Masses Compared

To allow for a comparison between the mass presented in the breathing zone derived from the still air conical model and the mass calculated by CFD modeling of the aircraft cabin, we need to select a case for comparison. For that purpose, the maximum presented mass of 1.9 µg from the aircraft CFD model data was selected. The entire range of the conical model masses (from 6 to 16 feet in distance) along with the worst case mass (light blue line) from the aircraft CFD model are presented in Figure 7.

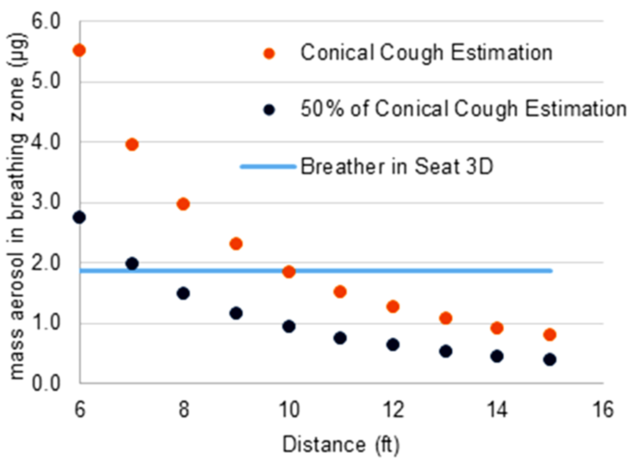

Figure 7. Still air conical model mass in breathing zone at various distances compared to an index passenger in Seat 3E producing mass in the breathing zone of a susceptible passenger in Seat 3D (light blue line, at 1.9 µg worst case).

Both the full mass presented in the breathing zone for the still air conical model and a 50% reduction value are shown in Figure 7. The mass presented to the breathing zone of each seat location in the BSI 737 Aircraft Cabin CFD model was compared to the mass predicted by the 50% conical model at various distances. As can be seen in Figure 7, the worst case for the aircraft indicates that the seat next to the cougher experiences less mass than a person seven feet away from an index person in the 50% conical model. The masses presented to the breathing zone for each seat location on the aircraft are binned by their engineered physical distance equivalence when compared to the conical model and presented in Figure 8.

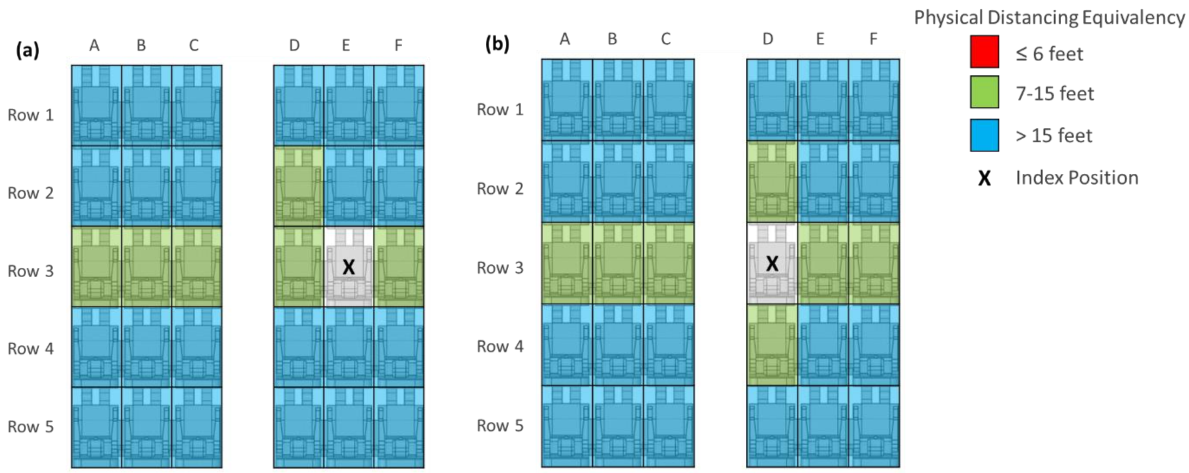

Figure 8. Binned mass pseudo-color seating map for two positions of the cougher in the aircraft cabin; cougher in seat 3E at left and cougher in seat 3D at right. 3F was held for brevity, but has similar results.

Limitations

The number of potential scenarios that could be studied is large. While this study was not exhaustive, the intent was to provide the engineered physical distance between individuals in seat pairs on an aircraft for common seating positions in a single-aisle airplane. It may be that the conical model is an overestimate of the material reaching the breathing zone of a nearby susceptible person, and for that reason the 50% reduction data set (Figure 7) for the conical model was used as a more conservative estimator to generate Figure 8. In addition, it is important to remember that for the conical model, only 47% of the original mass of the cough was used after removal of particles greater than 10 µm in diameter, adding another layer of conservatism to the analysis.

There are also factors that may make the still air conical model an underestimation of mass presented in the breathing zone of a nearby susceptible person. These factors may also contribute to the variability in mass presented to the breathing zone in an environment where the air is more still than on an aircraft. Some of the many considerations that might cause the conical model to be too low include:

(1) The convection heat plume surrounding a person (an average human radiates at approximately 70 Watts) may entrain more of the cough particles, bringing them into the breathing zone.

(2) The location of an air inlet and return air vent has the potential to affect and reduce the engineered physical distance between individuals.

(3) The air inlets to a room may provide other opportunities for entrainment of cough particles, thus driving up the concentration of cough particles in certain parts of the room.

(4) Obstacles in the environment may contribute to changes in airflow.

(5) Lack of filtration may allow particles to be recirculated by the environmental control system of a building.

Variation may also result from individuals being generally freer to move around, in ways that may increase or decrease the mass presented in the breathing zone from an index person coughing nearby. In particular, in a non-aircraft environment, people may or may not be facing one another.

The number of conditions that might be studied in systems similar to those discussed in this paper is large. This study was based on the conical model and therefore is a rough estimate. The intent was to provide a quantitative comparison of the mass of particles presented in the breathing zone of a susceptible person in both the aircraft and an environment where the engineering features of the aircraft are not present, i.e., the still air conical model. Effects touched on but not fully explored for the aircraft include the following items, which are listed in decreasing order of potential magnitude of effect:

(1) Actions of both index and susceptible persons, e.g., personal hygiene when coughing, the proper or improper use of masks, and moving around the cabin.

(2) Cabin environment defined by the operator and airport, e.g., aircraft air supply available and used while on the ground.

(3) Actions taken more generally by all passengers, e.g., luggage under seats, tray table up or down, use of Personal Air Outlets (PAOs), and not blocking return air grilles.

(4) Cabin configuration, e.g., seat pitch, galley separators, lavatory locations, lounge seating, and first/business/coach class seating arrangements.

(5) Changes in the cabin environment caused by the process of flight, e.g., changes in the percent relative humidity and temperature.

Future Work

Myriad factors defined by human behavior may affect air flow and the plume generated by an index person coughing. This study was configured as stated in the methods section and the values calculated are for those configurations only. As a perturbation study, it only addresses the exposure over the time period necessary to remove the cough particles from the environment. Using a method to estimate the total mass of inhaled particles over time for both continuous (e.g., breathing or talking) and discontinuous (e.g., coughing) processes may improve our understanding of the risk of infection. As yet, however, the number of virus particles per mass exhaled required to cause an infection has not been determined with sufficient rigor for COVID-19.

In the future, the study of other factors that may influence the spread of respiratory disease in both lower airflow and high airflow aircraft environments should be pursued. Those studies might include the analysis of continuous processes like breathing and talking, both of which were considered while preparing these studies. However, the mass available over time for inhalation was deemed smaller than that for a cough, thus the focus of the data and analyses presented herein.

The caveat for future studies is that most researchers will not have access to accurate models without the help of aircraft ECS system designers. To that end, partnering with aircraft manufacturers would be of great benefit to both experimentalists and CFD modelers. In addition, the computational equipment and software licenses required to run such simulations, in a reasonable period of time, are limiting for many researchers.

Current work by this team (to be presented in the near future) using a CFD model of an indoor commercial space will provide a more accurate estimate of the mass presented in the breathing zone for locations other than aircraft. It is expected that when compared to the simple conical model, the CFD model of indoor spaces will show significant variability in the mass presented to the breathing zone of susceptible nearby persons. A person's position in relation to the direction of airflow and the index person in an indoor commercial space may indeed determine the severity of exposure; thus adding to the variability in mass presented in the breathing zone in environments with more fluid conditions, human factors and lower airflows.

Conclusion

This paper calculates the engineered physical distance between individuals in seat pairs on an aircraft. To do this, the mass of particles presented in the breathing zone after an index person's cough is estimated for two environments: the aircraft cabin (via CFD modeling) and in still air (via a conical model). The maximum mass of expiratory particles that a passenger on an aircraft experiences in their breathing zone after cough by a nearby passenger is 1.9 µg. This mass aligns with the mass delivered by a conical model in still air at a distance of approximately seven feet. The distance between seats on an aircraft (~17.5 inches) is the engineered physical distance equivalent to a physical distance in still air of greater than 7 feet.

This result is due to the engineering controls on modern aircraft that include: airflow much higher than in typical indoor spaces; directional downward-flow designed for minimal fore/aft airflow; HEPA filtration that removes 99.97% of particles from supplied air; separation of rows by high-back seats; and positioning of passengers so that they do not face one another for the majority of the flight. The environmental control system in the aircraft provides an engineered physical distance for adjacent passengers which is an important layer of protection against airborne transmission of disease in the airplane cabin. The cabin and environmental control system designs coupled with multiple layers of protection and other safeguards throughout the travel journey, such as wearing a face mask, help mitigate the risk of disease transmission in the air travel system.

The layered approach to protections designed to combat the transmission of respiratory diseases has proven valuable in many environments. Physical distancing, ventilation, face coverings, personal protective equipment, frequent hand washing and surface disinfection are all important components in the control of respiratory disease. As with any redundancy factor for the improvement of reliability, no one control on its own can be as effective as all controls combined.

Acknowledgements:

The authors wishes to thank Ted Wu, Andrew Clark, Matt Schwab, Chao-Hsin Lin, Angela Davis, Steve Baughcum, Kay Blohowiak and Jill Seebergh for many productive discussions and access to CFD data. The authors also wish to acknowledge ANSYS™ for providing licenses for their Fluent™ platform software to support the Confident Travel Initiative studies.

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