Part 2

Minimizing COVID-19 Transmission in High Occupant Density Settings

BY DAVID ROTHAMER, PH.D.; SCOTT SANDERS, PH.D.; DOUGLAS REINDL, PH.D., P.E., FELLOW ASHRAE; TIMOTHY BERTRAM, PH.D.

This article is the second in a two-part series aimed at quantifying strategies to reduce the probability of infection by airborne disease in the indoor environment. It focuses on the virus that causes COVID-19, SARS-CoV-2. A modified form of the Wells-Riley model is used to predict the conditional probability of infection within high occupant density indoor environments such as classrooms. Results are presented for three distinct airborne exposure scenarios and a range of protective measures that include facility-related factors such as air change rates and in-room recirculating air filtration, and the occupant-related factor of masks with varying levels of effective filtration efficiency.

Introducing the Wells-Riley Model

In Part 1[1] of this series in the May *ASHRAE Journal*, we briefly introduced the Wells-Riley model,[2] which predicts the conditional probability of infection, P, based on a susceptible individual receiving a quanta dose, D_q, sufficient to cause infection as:

$$P = 1 - \exp(-D_q) \qquad (1)$$

where the infectious quanta dose, D_q, is quantified by

$$D_q = \bar{n}_q \ \dot{V}_b t_D (1 - \eta_{f,M_{inh}}) \qquad (2)$$

and *where*

D_q = infectious dose, quanta

$\bar{n}_q$ = average concentration of infectious quanta (i.e., aerosols uniformly distributed throughout the

David Rothamer, Ph.D., is the Robert Lorenz Professor of mechanical engineering, Scott Sanders, Ph.D., is a professor of mechanical engineering, Douglas Reindl, Ph.D., P.E., is a professor of mechanical engineering, and Timothy Bertram, Ph.D., is professor of chemistry at the University of Wisconsin, Madison, Wis.

space and carrying a viral or bacterial payload) within the room, quanta/m^3 (quanta/ft^3)

$\dot{V}_b$ = breathing rate of a susceptible person, m^3/h (ft^3/min)

t_D = occupant time duration in the room, h (min)

$\eta_{f,M_{inh}}$ = effective filtration efficiency of mask during inhalation.

In the present analysis, the infectious quanta are assumed to be SARS-CoV-2 contained within small aerosol droplets. We consider two breathing rates reflective of occupants in a classroom: an instructor at a breathing rate of 1.38 m^3/h (0.818 cfm) and students at a breathing rate of 0.540 m^3/h (0.318 cfm) based on values reported by Jimenez.[3] With the current emphasis on individuals wearing masks indoors, we include the reduction of inhaled quanta by a susceptible individual wearing a mask with an effective filtration efficiency during inhalation of $\eta_{M_{inh}}$. We measured mask effective filtration efficiencies and reported those results in Part 1 of this series. The infectious quanta dose is directly proportional to average quanta concentration in the space, occupant breathing rate, occupant time duration within the space and the penetration of quanta that breach a mask or face covering.

Assuming the room is well mixed, the average concentration of infectious quanta within the room, $\bar{n}_q$, will depend on the number of infectious individuals actively shedding virus, N_I, the rate of each individual's quanta emission, $\dot{q}$, room volume, V_R, occupant time duration in the room, t_D, effective mask filtration efficiency during exhalation, $\eta_{m_{exh}}$, and aerosol loss rate, λ. For the present analysis, we utilize separate quanta emission rates for the instructor (110 quanta/h) and student (19.1 quanta/h), based on values reported by Jimenez.[3]

Conceptually, it makes sense that an instructor who is speaking loudly and frequently would have a higher quanta emission rate compared to a student who is speaking infrequently and more quietly. Including the effective filtration efficiency of a mask functioning to reduce the quantity of exhaled infectious quanta, the net emission rate of quanta for infected individuals actively shedding in the room, $\dot{Q}$, becomes

$$\dot{Q} = N_I \dot{q}\left(1-\eta_{f,M_{exh}}\right) \tag{3}$$

where

$\dot{Q}$ = net emission rate of quanta for infected individuals actively shedding in the room, quanta/h

N_I = number of infectious individuals actively shedding virus

$\dot{q}$ = quanta emission rate of each infectious individual, quanta/h

$\eta_{f,M_{exh}}$ = effective filtration efficiency of a mask during exhalation.

Miller, et al., incorporated a first order loss rate of quanta due to various mechanisms that include dilution ventilation, aerosol deposition onto surfaces and virus decay into the calculation of the average concentration of infectious quanta in the room:[4]

$$\bar{n}_q = \frac{\dot{Q}}{\lambda V_R}\left[1-\frac{1}{\lambda t_D}\left(1-e^{-\lambda t_D}\right)\right] \tag{4}$$

where

λ = first-order loss rate comprising the various mechanisms that "remove" quanta from the room air

V_R = room volume, m^3 (ft^3).

The first-order loss rate can be expressed as the sum of individual losses:

$$\lambda = \lambda_{OA} + \lambda_{dist} + \lambda_{filtration} + \lambda_{filtration,portable} + \lambda_S + k \tag{5}$$

where

λ_{OA} = dilution effect associated with the volumetric flow rate of outdoor air, $\dot{V}_{OA}$, being dispersed into the room volume, V_R, $(\dot{V}_{OA} / V_R)$, h^{-1}

λ_{dist} = deposition of quanta in the return air distribution system, h^{-1}

$\lambda_{filtration}$ = removal of quanta due to filtration $\left(\eta_f \times \dot{V}_{SA} / V_R\right)$, h^{-1}

$\lambda_{filtration,\ portable}$ = removal of quanta due to in-room portable filtration unit $(\eta_{f,portable} \times \dot{V}_{portable} / V_R)$, h^{-1}

$\eta_{f,\ portable}$ = filtration efficiency of in-room air purifying filtration unit

η_f = central station supply air handling unit filtration efficiency

$\dot{V}_{portable}$ = volume flow rate of in-room portable filtration unit, if present, m^3/h (ft^3/h)

$\dot{V}_{SA}$ = supply air volume flow rate, m^3/h (ft^3/h)

λ_S = loss rate due to quanta settling, which can be expressed as the aerosol's settling velocity, V_{TS}, divided by the height where quanta are emitted, h^{-1}

k = rate of inactivation of the quanta, h^{-1}.

Additional loss mechanisms that may be applicable to a given situation can be added to *Equation 5*.

We use this modified version of the Wells-Riley model to predict the conditional probability of infection for susceptible individuals being exposed to infectious SARS-CoV-2 quanta generated by a single individual ($N_I = 1$) actively shedding virus-laden aerosols into a classroom space. The efficacy of various protective measures that aim to reduce infection risk are then quantified by determining how they individually and in combination impact the predicted conditional probability of infection. Further details on the analysis are provided by Rothamer, et al.[5]

Assessment of Measures to Prevent Airborne Transmission of COVID-19

Using the aerosol behavior characterized in the classroom, mask effective filtration efficiency data and other measured mechanical system data as input to the Wells-Riley model, we can quantify the conditional probability of infection for various protective measures using scenarios where one of the classroom's occupants is COVID-19–positive and actively shedding. The conditional probability of infection represents the probability for any one person being infected during any one event (e.g., a scheduled class meeting period). The conditional probability of infection is evaluated for the following three distinct exposure scenarios:

Scenario A: Infectious instructor with a quanta emission rate, $\dot{q}_I$, of 110 quanta/h and the corresponding calculated conditional probability of a student being infected when the student's breathing rate, $\dot{V}_{b,S}$, is 0.540 m^3/h (0.318 cfm).

Scenario B: Infectious student with a quanta emission rate of 19.1 quanta/h and the corresponding calculated conditional probability of the instructor being infected when the instructor's breathing rate, $\dot{V}_{b,I}$, is 1.38 m^3/h (0.818 cfm).

Scenario C: Infectious student with quanta emission rate, $\dot{q}_S$, of 19.1 quanta/h and the corresponding calculated conditional probability of another student being infected when that student's breathing rate is 0.540 m^3/h (0.318 cfm).

As noted in the three scenarios, the quanta emission rate, $\dot{q}$, is higher for the instructor who is speaking loudly and frequently compared to the student who is, generally, seated and speaking infrequently. Similarly, the breathing rate for individuals is proportional to their metabolic activity level, so the breathing rate, $\dot{V}_b$, will be higher for the instructor and lower for the student.

For each of the three exposure scenarios, a range of protective measures are evaluated for their ability to decrease the likelihood of an infection via airborne route. The protective measures include:

a. Total air change rate for the room expressed as air changes per hour ($N_{ACH} = \dot{V}_{SA} / V_R$);

b. Airflow rate circulating through in-room air purifying filtration unit(s); and

c. All occupants equipped with:
  i. No mask;
  ii. One of the previously mentioned masks (alone); and
  iii. One of the previously mentioned masks + mask fitter (see "Types of Masks and Braces Tested" sidebar).

Table 1 provides values of both fixed and variable parameters used to determine the conditional probability of infection.

Figure 1 shows the conditional probability of infection as a function of mask effective filtration efficiency for the three scenarios described above, assuming one infectious individual present in the room for a 60 minute duration and at a baseline room air exchange rate

Types of Masks and Braces Tested

They include a commercial four-ply knit cotton mask (KCM); a three-ply spunbond polypropylene mask designed by the University of Wisconsin–Madison Emergency Operations Committee (EOCM), a single-use three-ply disposable mask with a meltblown polypropylene center ply medical procedure mask (PM); and an ASTM F2100 Level 2 rated surgical mask (SM).

In addition, external braces tested include the UW fitter (U) and a commercial brace (C).

of N_{ACH} = 1.34 h^{-1}. For each of the scenarios, the mask effective filtration rate of 0 corresponds to the no-mask baseline for all room occupants.

Unremarkably, Scenario A (instructor infectious with student susceptible) had the highest trajectory of conditional probability of infection due to the higher quanta emission rate for the instructor. As the mask effective filtration efficiency increases, the conditional probability of infection decreases modestly until filtration efficiencies greater than about 0.6 (60%) are reached, after which it decreases rapidly with incremental improvements in filtration efficiency.

At a mask effective filtration efficiency of 0.5 (50%), the conditional infection probability is reduced by a factor of 4 relative to the no-mask baseline. With all occupants wearing a mask with an effective filtration efficiency of 0.9 (90%), the conditional infection probability is reduced by a factor of 100 relative to the no-mask baseline. This is due to the 10× decrease in quanta discharged into the room due to mask capture combined with the 10× decrease in quanta inhaled through the mask, resulting in a total reduction of a factor of 100.

Figure 2 shows the effect of ventilation rate in a well-mixed room on the conditional probability of infection when no occupants are wearing masks. As the ventilation rate increases from the no airflow case, the conditional probability of infection decreases at a somewhat rapid rate, but then begins to level out. For example, increasing the ventilation rate by a factor of ~3.8, from the baseline case of 1.34 ach to 5.05 ach, yields a conditional probability of

TABLE 1 Fixed and variable parameters included in the modified Wells-Riley model to predict conditional probability of infection for each of the three scenarios.

PARAMETER	DESCRIPTION	VALUE	FIXED/VARIABLE	SOURCE
V_R	Room Volume	362.64 m^3	Fixed	Facility Information
N_{ACH}	Room Air Change Rate	1.34 h^{-1}	Variable	Current Study, Field-Measured
λ_S	Particle Settling Loss Rate	0.35 h^{-1}	Fixed	Current Study
k	Virus Decay (Inactivation) Rate	0.63 h^{-1}	Fixed	Buonanno, et al.,[6] and van Doremalen, et al.[7]
λ	Total Loss Rate	2.32 h^{-1}	Variable	$\lambda = N_{ACH} + \lambda_S + k$
t_D	Duration Occupant is in Room	60 min.	Fixed	50 min. Class Period + 10 min. Before/After
$\eta_{f,M}$	Effective Mask Filtration Efficiency	–	Variable	Baseline = 0, Other Values As-Measured

FIGURE 1 Conditional probability of infection for each of the three case scenarios as a function of effective mask filtration efficiency. KCM–knit cotton mask, PM–procedure mask, SM–surgical mask, EOCM–emergency operations committee mask, –C = commercial brace, -U = UW fitter.

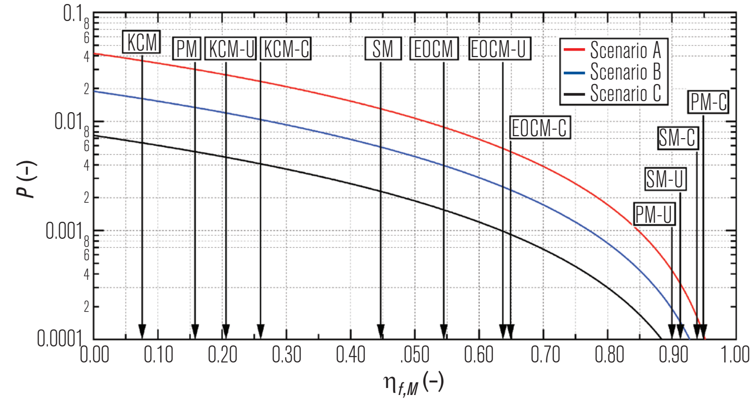
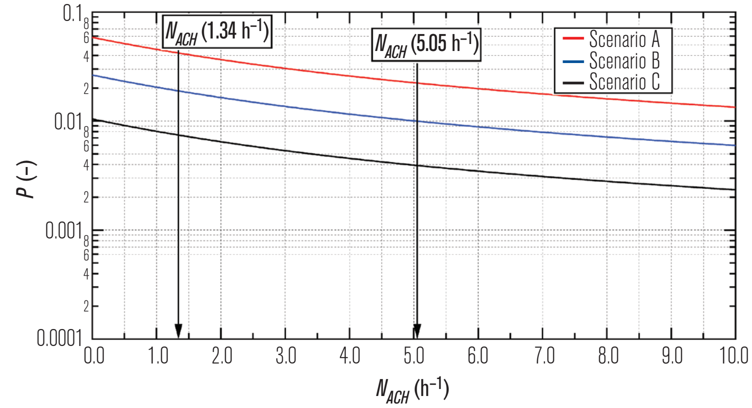


FIGURE 2 Conditional probability of infection for each of the three case scenarios as a function of ventilation rate in a well-mixed room.



infection reduction of only a factor of 2. Doubling the ventilation rate from 5 ach to 10 ach results in a conditional probability of infection reduction of only a factor of 1.7. This diminishing benefit agrees with the trend noted by Pantelic and Tham.[8]

Technologies such as in-room recirculating HEPA filtration units might be an option; however, in cases where the units maintain a well-mixed room airflow condition, these units have the same net effect as increasing room ventilation rates on decreasing the infection probability. Engineers need to begin rethinking traditional airside designs that function to achieve well-mixed room conditions and pursue alternative approaches that can deliver occupant comfort, acceptable indoor air quality and decreased risk of transmission of airborne pathogens.

The combination of modest increases in ventilation rates with masks is synergistic, as both are factors in the infectious quanta dose, D_q, given by *Equation 2*. For example, the combination of having occupants wearing knit cotton masks with either mask fitter and increasing the ventilation rate from 1.34 ach to 5.0 ach reduces the conditional infection probability by a factor of 3.4 relative to the no-mask baseline. This reduction is equal to the product of the reductions in infection probability for each individual measure. It is interesting to note that this combined reduction is greater than could be achieved by increasing room supply airflow from 1.34 ach to 10 ach.

The prospect of increasing ventilation rates to reduce infection probability is attractive because it can be "centrally" controlled, unlike ensuring that each occupant in the space has an appropriate mask that is properly fitted. Yet as we have already shown, occupants equipped with higher effective filtration efficiency masks can reduce the probability of infection far more than ventilation can. The real challenge with achieving and sustaining lower infection probability by relying on high mask filtration efficiency is that it is dependent on ensuring that all occupants properly and consistently don their own masks. Even with mask materials that have modest filtration capability, the use of mask fitters results in significant improvements in effective filtration efficiency and corresponding reductions in infection probability.

The time duration in the space is one of the factors that determine the infectious quanta dose, D_q, in *Equation 2*. The results shown thus far are for a fixed time duration in the space of 60 minutes. Increasing dwell time in the space increases the conditional probability of infection. Varying the time duration in the space by a factor of 2 with the 60 minute period as the base case proportionally changes the probability of infection proportionally (doubling the time duration in the space to 120 minutes doubles the probability of infection, while cutting the time duration to 30 minutes cuts the infection probability in half). At much longer duration times, the probability of infection increases nonlinearly.

Conclusions and Recommendations

We prepared an assessment of the various measures that offer the potential to reduce airborne transmission of the virus that causes COVID-19, SARS-CoV-2, for high occupant density spaces. The measures considered include both facility-related and occupant-related factors. Facility-related factors include physical distancing of occupants, room ventilation rates and the use of in-room recirculating HEPA filtration unit(s). Occupant-related factors include the use of various types of masks, both with and without external braces that function to improve mask fit. Face shields were evaluated early in the present study, but because they showed little efficacy in decreasing exposure to respiratory droplets, they were eliminated from further consideration.

Increased ventilation rates alone, or in tandem with in-room recirculating HEPA units, were not able to provide greater than approximately a 4× reduction in infection probability, for ventilation rates up to 10 ach. Mask effective filtration efficiency was found to have the single greatest impact for reducing the probability of infection via aerosol transmission. Occupants with masks having an effective filtration efficiency of 0.9 (90%) achieved a reduction in infection probability by a factor of 100× compared to the no-mask baseline. Although masks with high filtration efficiency ratings can provide significant reduction of infection probability, their fit to an individual is crucial to achieving performance.

The impacts of mask and HVAC control measures are independent, and combined reductions in infection probability are multiplicative. For example, the reduction in infection probability achieved with occupants wearing masks having a modest effective filtration efficiency of 0.55 (55%) (EOCM reusable spunbound polypropylene mask without a fitter) vs. the no-mask baseline is a factor of 4×. Increasing room airflow from 1.34 ach to 3 ach reduces infection probability by a factor of 2×. Both measures together yield a reduction in infection probability of a factor of ~8×. In-room recirculating HEPA air filtration devices have a similar effect at reducing the infection probability as increasing room air changes per hour.

Finally, it is important to note that our analysis does not include any medical assessment or appropriateness of the fitness of a given mask to be worn by an individual based on their physiology or medical condition, including their state of health.

References

1. Rothamer, D., S. Sanders, D. Reindl, T. Bertram. 2021. “COVID-19: Minimizing transmission in high occupant density settings, part 1.” *ASHRAE Journal* (5):10–17.

2. Riley, E., G. Murphy, R. Riley. 1978. “Airborne spread of measles in a suburban elementary school.” *American Journal of Epidemiology* 107(5):421–32.

3. Jimenez, J.-L. 2020. “COVID-19 aerosol transmission estimator.” Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder. https://tinyurl.com/s7xtc8tm.

4. Miller, S.L., W.W. Nazaroff, J.-L. Jimenez, A. Boerstra, et al. 2020. “Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event.” https://doi.org/10.1111/ina.12751.

5. Rothamer, D., S. Sanders, D.T. Reindl, T. Bertram. 2021. “Strategies to minimize SARS-CoV-2 transmission in classroom settings: combined impacts of ventilation and mask effective filtration efficiency.” Submitted to *Indoor Air*, preprint available at https://www.medrxiv.org/content/10.1101/2020.12.31.20249101v1

6. Buonanno, G., L. Morawska, L. Stabile. 2020. “Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications.” *Environment International* 145.

7. Van Doremalen, N., T. Bushmaker, D.H. Morris, M.G. Holbrook, et al. 2020. “Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1.” *New England Journal of Medicine* 382(16):1564–67.

8. Pantelic, J., K.W. Tham. 2012. “Assessment of the mixing air delivery system ability to protect occupants from the airborne infectious disease transmission using Wells–Riley approach.” *HVAC&R Research* 18(4):562–74. ■