Pitfalls of Using CO_2 Measurements as the Sole Indicator of IAQ and Airborne Transmission Risk

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ABSTRACT

Measurements of indoor CO_2 concentration provide valuable information about the indoor environment. Steady-state readings give a high-quality estimate of the ratio between generation (from occupants) and removal (via ventila-tion), while timeseries transient readings can be used to estimate ventilation rates. Both values are key to monitoring whether the HVAC system is maintaining adequate IAQ, and they can be used as inputs to models that estimate the risk of airborne transmission of infectious aerosols (e.g., containing SARS-CoV-2, which is responsible for the COVID-19 pandemic). The increasing availability of CO_2 sensors has led to a push to require CO_2 monitoring in schools and other public places. Such monitoring would provide valuable data to assess IAQ. Unfortunately, this push is also accompanied by a desire to define fixed thresholds of CO_2 concentration that separate "good" and "bad" IAQ as well as "safe" and "unsafe" conditions with respect to airborne transmission. Such approaches are misguided, as CO_2 concentration by itself does not provide sufficient context to fully evaluate IAQ or transmission risk. Our purpose in this paper is to explain why CO_2 concentration provides a partial but fundamentally incomplete picture of the indoor environment and to discuss the other key factors needed to perform a thorough assessment. For IAQ, we show how CO_2 is a surrogate only for human-sourced pollutants, which means a space with low CO_2 concentration could still have an unacceptably high concentration of building-sourced pollutants. For airborne transmission risk, we highlight the multiple removal mechanisms for infectious particles that have no effect on CO_2 concentration, meaning that the inherent risk in two spaces with identical CO_2 concentrations could vary by an order of magnitude or more depend-ing on which disinfection technologies are deployed. Our overall goal is to illustrate the right way to integrate CO_2 measurements into the overall management of IAQ and airborne transmission risk.

INTRODUCTION

COVID-19 and Airborne Transmission

In the wake of the COVID-19 pandemic, significant attention has been paid to how the operation of HVAC systems contributes to the risk of airborne disease transmission. Recognizing the role of airborne transmission in this pandemic and other seasonal outbreaks, many scientists have called for a "paradigm shift" focusing on improved ventilation to combat transmission of respiratory illnesses indoors (Morawska et al., 2021). This discussion has increased interest in indoor air quality (IAQ) more broadly, with infectious particles being just one (albeit very important) piece of the overall puzzle.

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The first recognition of the role of ventilation in airborne disease transmission came from the work of Wells (1955) and Riley et al. (1978), which gave a simple model relating occupancy, ventilation rate, and time to probability of transmission. A key limitation of this model is that it considers ventilation as the only removal mechanism, and later works showed how the effects of deposition, deactivation, filtration, and UV disinfection could be incorporated into this modeling framework (Buonanno et al., 2020; Bazant and Bush, 2021). These disparate mechanisms can be quantified and compared in terms of equivalent outdoor air (EOA) delivery (ASHRAE Epidemic Task Force, 2022). When analyzing the energy impact of these strategies, ventilation is often the most costly due to increased heating and cooling requirements (Abboushi et al., 2022), with filtration or UV disinfection being comparatively cheaper (Luo and Zhong, 2021; Azimi and Stephens, 2013). Unfortunately, this original emphasis on ventilation has persisted, leading to alternative strategies being consistently overlooked.

CO_2 Monitoring

In many buildings, there is no direct measurement of ventilation, due to the required flow sensors being expensive or otherwise deemed unnecessary. To make up for this missing data point, measurements of indoor CO_2 concentration have been implicitly used as a substitute. The fundamental physics of air exchange in a building means that CO_2 con-centration reflects the balance between sources (occupants) and sinks (outdoor-air ventilation), and internet-enabled sensors have made this data very easy to record (Peng and Jimenez, 2021; Bazant et al., 2021). While this infor-mation is certainly valuable, it is unfortunately common to make a leap directly from CO_2 concentration to airborne transmission risk, which generally ignores other sources of EOA. For example, Boston Public Schools has mandated IAQ monitoring (including CO_2, CO, PM, temperature, and humidity) in each occupied space, and the data is made publically available via an online portal (Boston Public Schools, 2022). In an associated document, the district does state that “it is important to note that CO_2 does not directly indicate risk of exposure to COVID-19” because CO_2 fails to account for other mitigation strategies. Nevertheless, any users visiting the IAQ dashboard are met with summary CO_2 readings presented with a simple color-coded “Typical / Moderate / High” classification using fixed thresholds (boundaries at 1000 and 2000 ppm), which means this “important” caveat is likely to be missed by most visitors.

Going a step further, some governments are considering requirements to make CO_2 monitoring mandatory in certain environments. The state of California has recently passed legislation requiring that “mandatory standards for carbon dioxide monitors in classrooms” be included in the next update of state building codes, motivated both to improve student cognition and to minimize exposure to airborne pathogens. Indeed, some studies have demonstrated cognitive impairment at moderate CO_2 concentrations (1,000 to 2,500 ppm), but effect varies significantly by task, and overall results are somewhat inconclusive (Satish et al., 2012; MacNaughton et al., 2015). On the other hand, the importance of a multifaceted response to COVID-19 and airborne transmission in general has already been recognized (ASHRAE Epidemic Task Force, 2021), which is somewhat inconsistent with guidelines focusing primarily on CO_2. Other governments are moving further in this direction, for example with Belgium mandating CO_2 monitoring in pub-lic places that are then labeled based on performance. These labels may account for other actions besides ventilation, but the current standard labels are based primarily on CO_2 concentration. Thus, building managers may unnecessarily focus on ventilation to remain in compliance, to the detriment of other more efficient courses of action.

Paper Overview

For its part, ASHRAE has recognized the shortcomings of CO_2-focused analysis, stating that “many applications of indoor CO_2 do not reflect a sound technical understanding of the relationship between indoor CO_2 concentrations, ventilation, and IAQ” (ASHRAE, 2022). These concerns are particularly relevant, as ASHRAE is currently developing a new standard “to establish minimum requirements for control of infectious aerosols” indoors (ASHRAE, 2023). Within that context, the goal of this paper is to present potential pitfalls of assessing airborne transmission risk and IAQ using CO_2 measurements alone. We start by providing an overview of mass-balance-based modeling of IAQ and airborne transmission risk. We then discuss three different types of pitfalls that arise from focusing too much on CO_2, illustrating them with real-world data and providing suggestions to avoid them. We then conclude with a brief summary.

MODELING

Contaminant and CO_2 Concentration

Assuming the concentration C of a given contaminant is uniform throughout a space with total volume V, the time evolution of its concentration is given by

$$V\frac{dC}{dt} = \underbrace{N_{\mathrm{occ}}g_{\mathrm{occ}} + g_{\mathrm{bkgd}}}_{\text{Generation}} - \underbrace{\lambda_{\mathrm{decay}}VC}_{\text{Removal}} + \underbrace{f_{\mathrm{OA}}(C_{\mathrm{OA}} - C) + f_{\mathrm{recirc}}(C_{\mathrm{recirc}} - C)}_{\text{Net Flow}} \tag{1}$$

The generation of each contaminant may come from occupants (via the per-occupant rate g_{occ} scaled by the number of occupants N_{occ}) or from the space itself (with rate g_{bkgd}), while direct removal can generally be assumed to follow a first-order decay rate (quantified as λ_{decay} based on the specific mechanisms). The remaining two terms account for net exchange of the contaminant from the outdoors (via outdoor-air flow f_{OA} with concentration C_{OA}) or from other spaces within the building (via recirculation flow f_{recirc} at concentration C_{recirc}). Whether these flows are a net source or sink of the contaminant depends on the relative concentrations. For a given contaminant species, various terms may be zero, which means its concentration may or may not be correlated with that of other species.

For the specific case of CO_2, we note that most spaces do not have a background generation rate (i.e., $g_{\mathrm{bkgd}} \equiv 0$) and there is no removal mechanism besides ventilation (i.e., $\lambda_{\mathrm{decay}} \equiv 0$). In addition, it is common (though not universal) that recirculation is insignificant, either because there is no recirculation (i.e., $f_{\mathrm{recirc}} \approx 0$) or the concentration difference is small (i.e., $C_{\mathrm{recirc}}^{\mathrm{CO_2}} \approx C_{\mathrm{CO_2}}$) Making these simplifications and assuming the measured concentration $C_{\mathrm{CO_2}}$ is at steady state, we thus have the relationship

$$C^{\mathrm{CO_2}} - C_{\mathrm{OA}}^{\mathrm{CO_2}} = N_{\mathrm{occ}}g_{\mathrm{occ}}^{\mathrm{CO_2}}/f_{\mathrm{OA}} \tag{2}$$

From the form of (2), we see that the measured CO_2 concentration (or more precisely, its *excess* above outdoor CO_2 concentration) essentially gives a measurement of the outdoor-air ventilation per person within the space. Thus, if one of those two quantities is known, the other can be estimated using the measured CO_2 concentration via this relationship. In cases where both quantities are unknown but approximately time-invariant, both values can be inferred during dynamic transitions by fitting an exponential relaxation to the transient measurements (Kabirikopaei and Lau, 2020; Risbeck et al., 2023).

Although we refer to CO_2 as a "contaminant," we note that it does not pose any health risks to occupants by itself, with time-weighted exposure limits set at 5,000 ppm (US Occupational Safety and Health Administration, 2019), which should be much higher than in most spaces. Rather, CO_2 is intended as a proxy for human-sourced indoor pollutants. It is chosen primarily because it is much easier to measure than other species and thus it provides an indirect estimate for quantities that would be much more expensive to measure directly. However, as we will show later, it is fundamentally an imperfect proxy for any contaminants (including infectious particles) that have alternative mechanisms of generation or removal.

Airborne Transmission Risk Equivalent Outdoor Air

Since the onset of the COVID-19 pandemic, there has been increased interest in modeling airborne pathogens as a new class of contaminant. The use of mass-balance models for airborne transmission dates back to Wells (1955), with many generalizations since. Assuming that these pathogens are found in aerosols exhaled by infectious occupants, the effective concentration follows a model similar to (1). The total dose of infectious particles received across all occupants can be inferred from this concentration, which can then be used to estimate the transmission rate (Risbeck et al., 2022a). For our purposes, we consider the primary risk metric to be the reproductive number $\mathscr{R}$, which gives the average number of transmission events caused by each infector. At steady state, we have the relationship

$$\mathscr{R} = \alpha N_{\mathrm{occ}}\tau/f_{\mathrm{EOA}} \tag{3}$$

in which τ is the amount of time each infector spends in the space, f_{EOA} is the effective infectious-particle removal rate quantified in terms of equivalent outdoor air (EOA) flow, and α is a proportionality constant related to breathing

Table 1: Table of EOA formulas and typical range for various disinfection mechanisms in indoor spaces. Note that values in ACH are calculated as f_{EOA}/V using space volume V.

Mechanism	f_{EOA} Formula	Range (ACH)	Notes
Outdoor-Air Ventilation	f_{OA}	0.5 to 10	Only disinfection source considered in Wells (1955) and Rudnick and Milton (2003).
Recirculated Filtration	$\eta_{\mathrm{filter}} f_{\mathrm{recirc}}$	0 to 10	η_{filter} is the effective filtration efficiency for infectious aerosols (ASHRAE Epidemic Task Force, 2022).
Passive Deposition	Av_{dep}	0.3 to 0.9	A is floor area, and v_{dep} is the effective particle deposition velocity, which depends on relative humidity via the particle size distribution (Bazant and Bush, 2021).
Passive Deactivation	$k_{\mathrm{deact}}V$	0 to 0.6	k_{deact} is the passive deactivation rate, which depends on relative humidity (Morris et al., 2021).
Air-Cleaning Devices	$\eta_{\mathrm{device}} f_{\mathrm{device}}$	1 to 10	η_{device} is the effective disinfection efficiency for the device and f_{device} is the total volumetric flow through the device. Note that this calculation is the same as the "clean air delivery rate" for appropriately sized particles (AHAM, 2020).
UV Irradiation	$ZI_{\mathrm{UV}}V_{\mathrm{UV}}$	1 to 25	Z is the pathogen's susceptibility factor, I_{UV} is the imposed UV intensity, and V_{UV} is the total volume of irradiated air (Kowalski, 2010).

rate, mask usage, and other considerations (see Bazant and Bush (2021) for details).

The key parameter in (3) related to the HVAC system is the EOA flow f_{EOA}, which gives the *total* of all deactivation or removal mechanisms infectious pathogens. We refer to these processes collectively as "disinfection," but it should be noted that many operate by simply removing the infectious particles from the air, rather than destroying the infectious pathogens within. Table 1 gives formulas and typical ranges to calculate EOA delivery for various disinfection mechanisms. If multiple sources are present in a given space, the total EOA delivery is calculated as their simple sum. Note that each source can be expressed as a corresponding EOA change rate $\lambda_{\mathrm{EOA}} := f_{\mathrm{EOA}}/V$ by dividing by the space volume. Many of these sources require additional energy consumption to employ, and thus energy cost can be optimized by choosing EOA sources with the lowest relative energy consumption (Risbeck et al., 2021).

The main utility of (3) is that it can be used to quantitatively limit the risk of airborne transmission across spaces (Risbeck et al., 2023). For example, given the average EOA delivery rate f_{EOA} and a desired upper limit on $\mathscr{R}$, the total number of allowed occupant hours can be calculated. Of course, given the uncertainty in the parameters (primarily the proportionality constant α), limiting *absolute* risk can require a conservative approach. However, comparing *relative* risk among different spaces or operating scenarios (especially when the α values are the same) can be performed with much more confidence.

An important caveat is that (3) considers only transmissions associated with aerosols that have had time to mix throughout the space. If occupants are directly breathing exhaled air from other occupants, then there is elevated exposure risk due to the higher concentration of infectious particles in this air (Abkarian et al., 2020; Bhagat et al., 2020). Under mixing ventilation conditions or when occupants are wearing masks, experiments have shown that natural buoyancy causes exhaled air to rise above the breathing zone within 4 feet of horizontal separation (Zhang et al., 2022), which means this short-range transmission is generally small relative to (3) in these cases. However, in other circumstances (e.g., restaurants or face-to-face meetings), the calculation will need to be supplemented to include this additional short-range risk (Bazant and Bush, 2021).

CO_2-Based Transmission Model

A key challenge in applying the transmission-risk model (3) is that it requires a count of the number of occupants, which is often not readily available in most spaces. To address this limitation, Rudnick and Milton (2003) proposed that the occupancy count could effectively be estimated from the measured CO_2 concentration. Mathematically, we

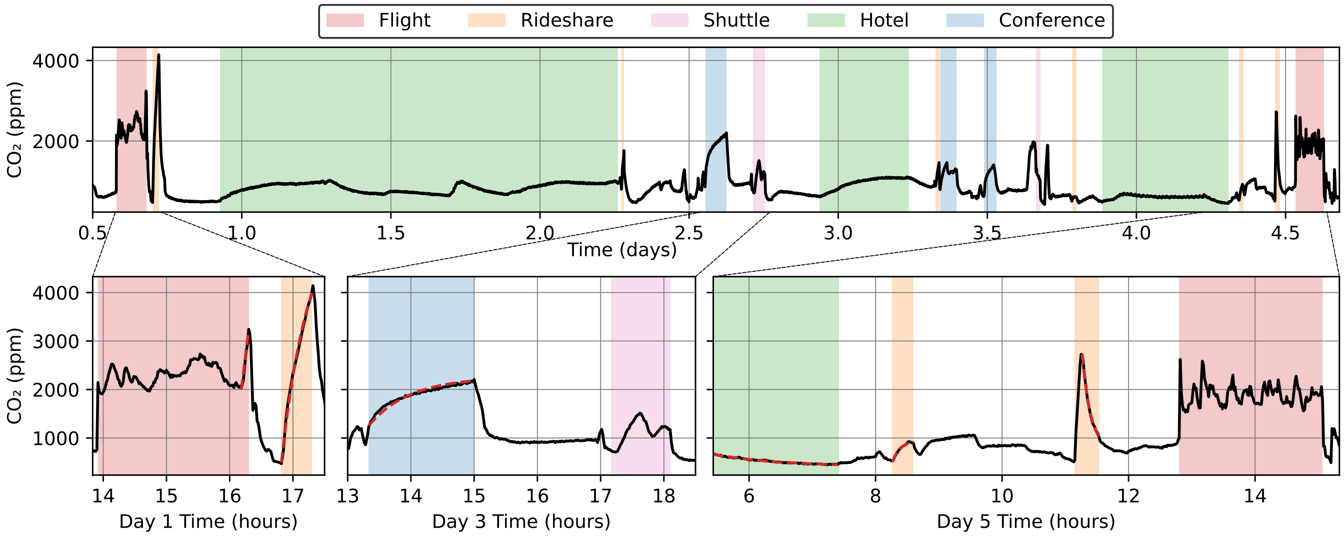


Figure 1: Timeseries CO_2 data from a 5-day trip by one of the authors. Shaded regions show periods where the sensor was known to be in a single location. Dashed red curves in the bottom axes show exponential fits to periods where occupancy and ventilation are assumed to be constant.

solve for N_{occ} in (2) and substitute into (3). Following this procedure gives the composite equation

$$\mathscr{R} \propto \frac{f_{\mathrm{OA}}}{f_{\mathrm{EOA}}}\left(C^{\mathrm{CO_2}} - C_{\mathrm{OA}}^{\mathrm{CO_2}}\right)\tau \tag{4}$$

The proportionality constant $\alpha / g_{\mathrm{occ}}^{\mathrm{CO_2}}$ varies with occupant activity level and mask usage but not any parameters of the HVAC system, so its exact value is not required to compare risk across spaces with similar occupant behavior.

CO_2-based transmission-risk models similar to (4) have been proposed in the past (Peng and Jimenez, 2021; Bazant et al., 2021), and the models are mathematically valid at steady state. However, some presentations do not sufficiently emphasize the inherent variability in key model parameters. In particular, the importance of the ratio $f_{\mathrm{OA}}/f_{\mathrm{EOA}}$ is generally understated; for example, the original model in Rudnick and Milton (2003) ignores it completely by assuming it is always equal to 1. As we will show in the following sections, such a simplification is not justified in most spaces and will fail to provide a full picture of the transmission risk in a given space.

PITFALLS AND ILLUSTRATIONS

Exposure Time

For most pollutants, the risk of negative outcomes to an individual depends on total exposure, which is determined not just by the *rate* of exposure (i.e., the concentration of the pollutant the individual experiences) but also the *duration* of that exposure. This time effect is captured by the parameter τ in (4) for airborne transmission risk, and it is relevant for other contaminants as well. The practical consequence is that acceptable exposure limits should account for both dimensions. To illustrate this relationship, we use CO_2 data collected by one of the authors during a trip to the 2023 ASHRAE Winter Conference. Throughout this period, the sensor was kept in the outer pouch of a backpack or in the author's hotel room. Figure 1 shows the timeseries data, annotated with specific events where the measurements were taken.

From these measurements, we see that the two flights have significantly higher CO_2 concentration than the rest of the trip. Assuming consistent EOA delivery in all cases (which is likely a poor assumption, as will be discussed in the next section), the instantaneous airborne transmission risk is also the highest during these periods. However, we note that these periods account for only four hours of the total trip. Indeed, the author spent roughly that much time in the conference venue on each of the three full days of the trip. (Note that the indicated "Conference" periods are where the measurement is from the same room, but the author did additional time at the venue.) Thus, for the *total* transmission risk of the flights to be equal to the total risk of the conference, the *instantaneous* risk on the flight would need to be at least three times that of the conference. Similarly, most of the rideshares show correspondingly high CO_2 concentration, but their total duration is less than two hours. Thus, to reduce transmission risk throughout the whole trip, the most effective place to apply additional disinfection is at the conference. This conclusion holds based on the simple time-based analysis discussed here, and it is further bolstered when accounting for difference in EOA delivery. Because an instantaneous CO_2 measurement captures only one dimension of this analysis, it is fundamentally incomplete.

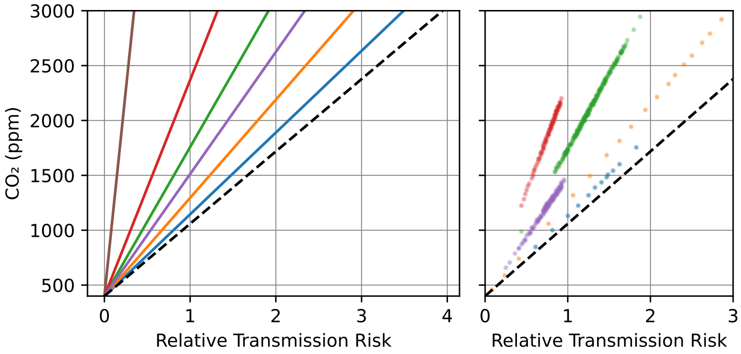
To avoid this pitfall, standards indended to limit airborne transmission risk or exposure to other indoor contaminants should account for the amount of time each occupant is likely to spend in that space. For example, requirements for places like schools and offices where occupants spend eight hours or more per day should be more stringent than requirements for transportation, stores, restaurants, and other places where less time is likely to be spent. Elevated risk of short-range transmission should also be included where relevant. These two dimensions are already considered for more acutely hazardous pollutants in the form of separate thresholds for instantaneous and time-weighted exposure (US Occupational Safety and Health Administration, 2019), and similar structure should be incorporated for airborne transmission and indoor pollutants.

Non-Ventilation EOA Sources

In the context of airborne transmission, we have seen that there are many different HVAC-based strategies for reducing risk. Among the available strategies, increased outdoor-air ventilation is often the most costly (Azimi and Stephens, 2013; Risbeck et al., 2022b; Abboushi et al., 2022), and it is also the only strategy that has a direct impact on CO_2 concentration. Thus, two different spaces with the same CO_2 concentration may have vastly different transmission risk (or vice versa), and trying to make that assessment based on CO_2 alone will significantly penalize spaces with other significant sources of EOA. To illustrate this variability, we further assess the data presented in Figure 1. A naive analysis based only on CO_2 would once again indicate that the two flights have significantly higher airborne transmission risk than any other event, but the full situation is much more nuanced and depends crucially on the sources of EOA present in that space.

To estimate airborne transmission risk in various conditions via (4), we need to know the outdoor-air ventilation and total EOA delivery in each space. For time periods where occupancy and ventilation are assumed to be reasonably constant, ventilation can be estimated by fitting (1) to CO_2 data to determine the unknown air-change rate f_{OA}/V, while for other periods we must assume values. During "Rideshare" events, we estimate between 2.0 and 7.5 ACH of ventilation, which is consistent with experimentally measured values depending on whether ventilation is active (Ott et al., 2008). For the "Airplane" case, we assume 16 ACH of ventilation and an additional 16 ACH of HEPA-filtered recirculated air (Kinahan et al., 2021). During conference events, we estimate roughly 2.5 ACH of ventilation, which we assume could be delivered in two different ways: first, by a mixed-air AHU system operating at 35% outdoor air with a MERV13; and second, by a dedicated outdoor-air FCU system with the same flows and MERV4 filters. Finally, for the "Hospital" case, we consider a hypothetical 2.5 ACH of ventilation supplemented by 25 ACH of EOA from far UV lamps, conditions which have been verified experimentally (Eadie et al., 2022). Figure 2 shows the dependence of transmission risk on CO_2 concentration for these scenarios. Note that risk is normalized to a value of 1 for a space with ventilation and occupant density per Standard 62.1 (ASHRAE, 2019) for "Public Assembly Spaces–Lobbies" assuming 35% outdoor air operation with a MERV8 filter.

From these relationships, we see that at the same CO_2 concentration, the two "Car" cases pose the highest transmission risk, followed by the two "Conference" cases with "Airplane" in between them, and finally with "Hospital" significantly below them. Thus, although the two flights had clearly the highest CO_2 concentration in Figure 1, the transmission risk accounting for all sources of EOA is similar to that of the indoor "Conference" spaces. (We note also that the well-mixed model likely overestimates transmission risk in the "Airplane" scenario, as airflows are specifically designed to minimize mixing between rows of passengers, and thus exhaled pathogens would be quickly removed from the air before spreading far from their source (Kinahan et al., 2021).) Another important observation is



	Name	Vent. (ACH)	Recirc. (ACH)	Filter Type	Extra EOA (ACH)
🟦	Car (High)	7.5	0.0	N/A	0.0
🟧	Car (Low)	2.0	0.0	N/A	0.0
🟩	Airplane	16.0	16.0	HEPA	0.0
🟥	Conference (AHU)	2.5	4.6	MERV13	0.0
🟪	Conference (FCU)	2.5	4.6	MERV4	0.0
🟫	Hospital	2.5	0.0	N/A	25.0

Figure 2: CO_2 concentration versus transmission risk for a variety of EOA scenarios. Lines in the left plot show the relationship per (4) assuming identical exposure time τ, while points in the right plot are taken from the timeseries data under the given conditions. Dashed line shows relationship assuming all EOA is from outdoor-air ventilation. Legend shows assumed ventilation, recirculation (with corresponding filter type), and extra EOA.

that there is a significant difference in transmission risk between the two “Conference” cases despite having the same airflows. The reason is that in the AHU system, the recirculated air is passed through a high-efficiency MERV13 filter at the AHU, which removes 86% of the infectious particles passing through it; by contrast, the recirculated air in the FCU system passes through MERV4 filters, which remove only 14% of infectious particles (ASHRAE Epidemic Task Force, 2022). This difference is *not* reflected in the CO_2 data, and indeed it would be difficult for anyone to assess without knowledge of the filter type. The remaining “Hospital” scenario is perhaps the most speculative scenario, in that far UV systems have not been widely deployed and are still undergoing experimental validation. Nevertheless, if the assumed EOA delivery is possible, transmission risk is much lower than the other cases regardless of the measured CO_2 concentration. Were performance assessed using CO_2 alone, the building manager may feel compelled to increase outdoor-air ventilation, which will increase energy costs, and depending on outdoor air quality, it might also hurt IAQ as we will illustrate next.

To avoid this pitfall, it is necessary to measure (or at least estimate) all sources of EOA and present this information simultaneously with CO_2 measurements. For example, both ventilation and total EOA should be presented as values in ACH that can be more readily compared across spaces. In addition, any qualitative rating system for transmission risk should account for these effects, e.g., using thresholds on the $\mathscr{R}$ value calculated using the simplified form of (4), rather than applying thresholds to the CO_2 measurement directly. Any regulatory requirements concerning CO_2 monitoring for airborne transmission control should make allowances for these other sources of EOA so that building managers can select the most cost-effective and energy-efficient disinfection strategies for their spaces.

Non-Occupant-Sourced Pollutants

As discussed with the general contaminant balance in (1), there are four potential sources of contaminants in a given space: occupants, air recirculated from other zones, outdoor air, and the space itself. For CO_2, only the first two are relevant, which means that any contaminants with significant sources from the latter two categories will often *not* be represented by CO_2. To illustrate this effect, Figure 3 shows plots of measured CO_2 concentrations and coincident measurements of other contaminants. This data was captured from a naturally ventilated classroom, which means that outside air is unfiltered and thus a significant source of particulates.

Starting with VOCs, we see that while there is clear correlation with CO_2 for much of the data, there are a significant number of samples where the two diverge. In fact, the measured samples with the highest TVOC concentration actually correspond to some of the lowest values of CO_2. Numerically, this results in a modest correlation coefficient of 0.66 for these variables. By contrast, we see that the PM data streams are almost completely uncorrelated with CO_2. Part of this behavior could be due to the use of an in-zone air filter during occupied hours, which means PM concentrations would be artificially reduced when CO_2 is elevated due to occupants. However, the primary explanation is

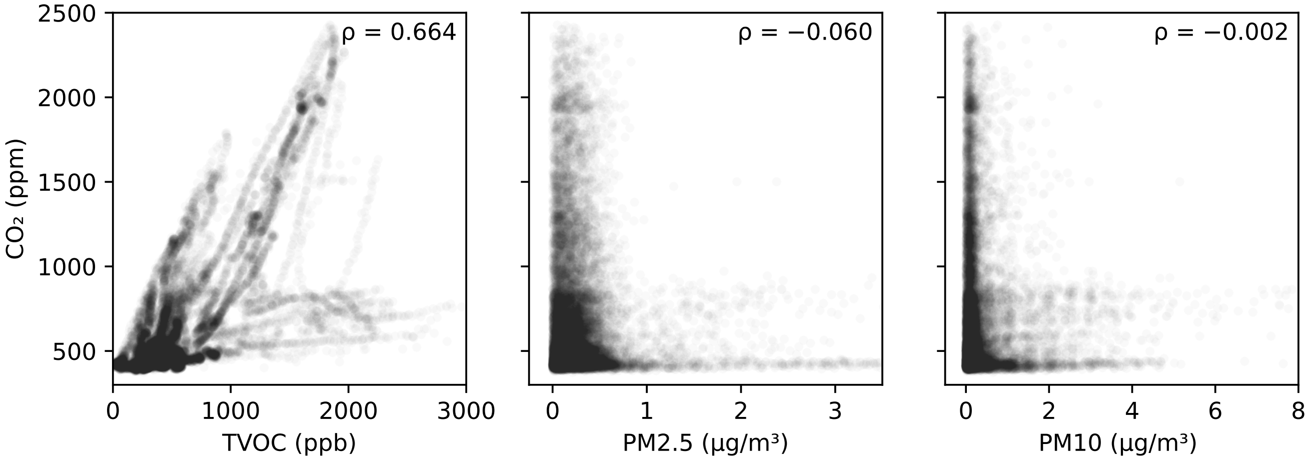


Figure 3: Scatter plots of IAQ metrics measured during nominally occupied hours over a four-week period in a naturally ventilated university classroom. ρ gives the value of the correlation coefficient for the two variables.

that since this contaminant is sourced primarily from outside, additional outdoor-air ventilation is actually detrimental to IAQ with respect to PM. Thus, both of these species illustrate how CO_2 gives a fundamentally incomplete picture of IAQ in many spaces.

To mitigate this pitfall, a possible solution is to measure additional IAQ metrics including VOCs and PM. These measurements will provide more direct proxies for harmful contaminants that are sourced primarily from outdoors or the building itself. Quality of this analysis could be further enhanced by taking the same measurements in the outdoor and return ducts to truly identify where contaminants are sourced. An added benefit is that this data can be used to estimate as-operated filtration efficiency and to calculate outdoor air fraction if it is not already measured. Where cost permits, the air in spaces can be sampled and evaluated with more sophisticated analytical techniques to identify the specific chemical and other pollutants present in a space, which facilitates a more informed selection of mitigation strategies.

CONCLUSIONS

In this paper, we have demonstrated possible pitfalls with using CO_2 as the sole or primary indication of airborne transmission risk and IAQ. The key pitfalls and possible solutions are as follows:

- Instantaneous concentration measurements give only the *rate* of exposure and do not account for the *duration*. Thus, limits should be adjusted based on the amount of time typical occupants will spend in a particular space.
- CO_2 concentration measurements do not account for other sources of EOA besides outdoor-air ventilation, which overestimates transmission risk for those spaces. Therefore, measurement and reporting requirements should include total EOA so that the CO_2 concentration can be put in the proper context.
- The concentration of contaminants not sourced from occupants is not directly reflected in CO_2 measurements, and increased ventilation can lead to *worse* IAQ in some aspects. Thus, these other contaminants should be measured and reported independently.

As recommendations and regulations for CO_2 monitoring are developed, it is important to keep these caveats in mind so that requirements are properly motivated and allowances are made for technologies other than ventilation. Only with proper guidance in this area will it be possible to keep indoor spaces safe, healthy, and energy-efficient.

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