# Development of an Indoor Carbon Dioxide Metric

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## ABSTRACT

Indoor carbon dioxide ($CO_2$) concentrations have been used for decades to purportedly evaluate indoor air quality (IAQ) and ventilation. However, many applications of $CO_2$ as a metric have reflected a lack of understanding of the connection between indoor $CO_2$ levels, ventilation and IAQ. In many cases, an indoor concentration of 1800 mg/m$^3$ (1000 ppm$_v$) has been used as a metric of IAQ and ventilation without understanding its basis or significance. After many years of effort trying to dissuade practitioners as well as researchers from using this value, or some other concentration, as a metric of ventilation and IAQ, the author has developed an approach to determine a $CO_2$ level that can be used as a meaningful indicator of the outdoor ventilation rate per person. Rather than a single $CO_2$ concentration for all spaces and circumstances, this paper describes an approach to estimating a space-specific $CO_2$ concentration from several relevant factors. The concept is based on an estimate of the $CO_2$ concentration that would be expected in a specific space type given its intended or expected ventilation rate per person, the number of occupants and the rate at which they generate $CO_2$, and the occupancy schedule. A calculation method is described for estimating the $CO_2$ concentration for a given space and the timeframe for achieving that concentration, which provides a more meaningful metric than a single value for all spaces.

## KEYWORDS

Building performance; carbon dioxide; indoor air quality; metrics; ventilation

## 1 INTRODUCTION

Indoor air quality (IAQ) is characterized by the chemical and physical constituents of air, plus other properties (e.g., thermal), that impact occupant health, comfort and productivity. The number of measurable airborne contaminants in most indoor environments is quite large, easily in the hundreds, and their impacts on building occupants is known for only a very small number. The large number of airborne contaminants, and their wide variation among buildings and over time, makes it extremely challenging to quantify IAQ conditions via a small number of parameters, let alone to distinguish between good and bad IAQ based on a single metric. There have been several efforts over the years to define IAQ metrics, but none have been shown to capture the occupant impacts of IAQ very well or have been accepted by the field (Hollick and Sangiovanni, 2000; Moschandreas et al., 2005; Jackson et al., 2011; Teichman et al., 2015).

Nevertheless, the indoor concentration of carbon dioxide ($CO_2$) has been widely promoted as a metric of IAQ and ventilation, in many cases without a clear understanding or explanation of what it is intended to characterize or a description of its application or limitations as a metric (Persily, 1997). At the simplest level, many practitioners use 1800 mg/m$^3$ (roughly 1000 ppm$_v$) as a metric, erroneously basing it on ASHRAE Standard 62.1 (ASHRAE, 2016a).

Despite numerous statements to the contrary, that standard has not contained an indoor $CO_2$ limit for almost 30 years (Persily, 2015a). The $CO_2$ concentration limit was removed based on the confusion that it caused and the fact that it is not a good indicator of ventilation or IAQ. There have been many papers, presentations and workshops that have attempted to clarify the meaning of indoor $CO_2$ concentrations and even to advocate that they not be used as IAQ and ventilation metrics. However, it appears clear that calls to stop using indoor $CO_2$ to characterize IAQ and ventilation are not succeeding. Instead, efforts to educate designers, practitioners and others in the field need to continue, and this paper proposes an approach to using indoor $CO_2$ concentrations as a metric of ventilation rate per person based on a thorough consideration of the relevant parameters that determine indoor $CO_2$ levels.

## 2 BACKGROUND ON INDOOR $CO_2$ CONCENTRATIONS

Indoor $CO_2$ concentrations have been prominent in discussions of ventilation and IAQ since the $18^{th}$ century, when Lavoisier suggested that $CO_2$ build-up rather than oxygen depletion was responsible for "bad air" indoors (Klauss et al., 1970). About one hundred years later, von Pettenkofer suggested that biological contaminants from human occupants were causing indoor air problems, not $CO_2$. Since that time, discussions of $CO_2$ in relation to IAQ and ventilation have evolved, focusing on the impacts of $CO_2$ concentrations on building occupants, how these concentrations relate to occupant perception of bioeffluents, the use of indoor $CO_2$ concentrations to estimate ventilation rates, and the use of $CO_2$ to control outdoor air ventilation rates (Persily, 2015b).

Indoor $CO_2$ concentrations are certainly relevant to the outdoor air ventilation rates per person specified in standards, guidelines and building regulations (CEN, 2007; ASHRAE, 2016a; ASHRAE, 2016b). These outdoor air requirements reflect more than 100 years of research, which first focused on the amount of ventilation needed to control odor associated with the byproducts of human metabolism, i.e., bioeffluents (Klauss et al., 1970). This research found that about 7.5 L/s to 9 L/s per person of ventilation air diluted body odor to levels judged to be acceptable by individuals entering the room from relatively clean air, i.e., unadapted visitors. Some of these experiments also included measurements of $CO_2$ concentrations, allowing examination of the relationship between $CO_2$ concentrations and body odor acceptability. The finding that about 8 L/s per person of ventilation controlled human body odor such that about 80 % of unadapted visitors found the odor to be acceptable was accompanied by the result that the same level of acceptability occurred at $CO_2$ concentrations about 1200 mg/m$^3$ above outdoors. For an outdoor $CO_2$ level of 600 mg/m$^3$, this concentration difference corresponds roughly to the commonly-cited indoor value of 1800 mg/m$^3$. (Note that outdoor levels have increased to 700 mg/m$^3$ or more since these odor acceptability studies were done (NOAA, 2018).) This body of research supports 1800 mg/m$^3$ of $CO_2$ as a reflection of body odor acceptability perceived by unadapted visitors to a building. Of course, there are many other important indoor air contaminants that are not associated with the number of occupants, and $CO_2$ concentration is not a good indicator of those contaminants.

ASHRAE Standard 62-1981 contained an indoor $CO_2$ limit of 4500 mg/m$^3$ for use when applying the performance approach to complying with the standard, i.e., the Indoor Air Quality Procedure. That limit was changed without written explanation to 1800 mg/m$^3$ in the 1989 version of the standard. That value was viewed by many a de facto standard without a sound understanding of its basis as an indicator of body odor acceptability to unadapted building occupants (Persily, 1997). This 1997 reference notes the existence of anecdotal discussions associating $CO_2$ concentrations in this range with occupant symptoms such as stuffiness and discomfort, also noting that peer-reviewed studies do not support these associations with the $CO_2$ itself. While several studies have shown associations of elevated $CO_2$ levels with symptoms, absenteeism and other effects (Apte et al., 2000; Shendell et al., 2004; Gaihre et al., 2014), these associations are likely due to lower ventilation rates elevating the concentrations of other more important indoor contaminants.

Indoor $CO_2$ concentrations are typically well below values of interest based on health concerns, though some recent work has shown evidence of impacts on human performance (Persily, 2015b). Two studies of individuals completing computer-based tests showed statistically significant decreases in decision-making performance at $CO_2$ concentrations as low as 1800 mg/m$^3$ (Satish et al., 2012; Allen et al., 2016). These experiments were carefully designed to expose the subjects to elevated $CO_2$ and not to other contaminants. However, other studies have not shown performance impacts at similar concentrations, therefore, it is premature to conclusively link $CO_2$ concentrations in this range with such occupant impacts (Zhang et al., 2016; Liu et al., 2017).

In summary, indoor $CO_2$ has not been shown to be a meaningful indicator of IAQ, and typical indoor levels do not have significant impacts on occupant health and comfort. Instead, this paper proposes using $CO_2$ as an indicator or metric of outdoor air ventilation rates per person. As discussed below, indoor $CO_2$ concentrations depend primarily on the rate at which the occupants generate $CO_2$ , the outdoor air ventilation rate of the space, the time since occupancy began, and the outdoor $CO_2$ concentration. Therefore, for indoor $CO_2$ to serve as a meaningful indicator of ventilation, all of these factors need to be considered.

## 2.1 Single-zone mass balance theory

The approach described in this paper, as well as many other discussions of indoor $CO_2$, employs a single-zone mass balance of $CO_2$ in the building or space of interest, which can be expressed as follows:

$$V \frac{dC}{dt} = Q\,(C_{out} - C) + G, \tag{1}$$

where $V$ is the volume of the building or space being considered, $C$ is the $CO_2$ concentration in the space in units of mg/m$^3$, $C_{out}$ is the outdoor $CO_2$ concentration, $t$ is time in hours, $Q$ is the volumetric flow of air into the building (space) from outdoors and from the building (space) to the outdoors in m$^3$/h, and $G$ is the $CO_2$ generation rate in the space in mg/h. Note that, in general, $Q$, $C_{out}$ and $G$ are functions of time, but they are assumed to be constant in this discussion. Also, air density differences between indoors and out are being ignored by using the same value of $Q$ for the airflow into the space (building) and out. Finally, this single zone formulation ignores concentration differences between building zones and the $CO_2$ transport that occurs between zones. This last assumption is not always valid, and its appropriateness in any application of Equation 1 must be considered.

The solution to Equation 1 can be expressed as follows:

$$C(t) = C(0)e^{-\frac{Q}{V}t} + C_{ss}\left(1 - e^{-\frac{Q}{V}t}\right), \tag{2}$$

where $C(0)$ is the indoor concentration at $t = 0$ and $C_{ss}$ is the steady-state indoor concentration. Note that the indoor concentration will only reach steady-state if conditions, specifically $Q$ and $G$, are constant for a sufficiently long period of time, which can be many hours as discussed below. In particular, a constant value of $G$ requires that the occupancy remain constant, and in many spaces occupancy will be too short or too variable for steady-state to be achieved. A convenient means of assessing whether steady-state is likely to be achieved is by considering the time constant of the system, which is equal to the inverse of $Q/V$ in Equation 2, i.e., the inverse of the air change rate. One can consider that the system is essentially at steady-state after three time constants. For example, for a space with an air change rate of 1 $h^{-1}$, steady-state will exist after three hours. For a space with an air change rate of 0.5 $h^{-1}$, it will take six hours.

## 2.2 $CO_2$ generation from building occupants

The ventilation and IAQ fields have long used the following equation to estimate $CO_2$ generation rates from building occupants (ASHRAE, 2017):

$$V_{CO2} = \frac{0.00276\, A_D\, M\, RQ}{(0.23RQ + 0.77)} \tag{3}$$

where $V_{CO2}$ is the $CO_2$ generation rate per person (L/s); $A_D$ is the DuBois surface area of the individual ($m^2$); $M$ is the level of physical activity, sometimes referred to as the metabolic rate or met level (dimensionless); and $RQ$ is the respiratory quotient (dimensionless). The respiratory quotient, $RQ$, is the ratio of the volumetric rate at which $CO_2$ is produced to the rate at which oxygen is consumed, and its value depends primarily on diet. Based on data on human nutrition in the U.S, specifically the ratios of fat, protein and carbohydrate intake, $RQ$ equals about 0.85 (Persily and de Jonge, 2017).

More recently, an approach to estimating $CO_2$ generation rates from building occupants based on concepts from the fields of human metabolism and exercise physiology has been described (Persily and de Jonge, 2017). This approach uses the basal metabolic rate (*BMR*) of the individual(s) of interest, which is the energy needed to sustain the basic functions of human life, including the function of cells, the brain and the cardiac and respiratory systems, as well as the maintenance of body temperature. The *BMR* value of an individual is a function of their sex, age and body mass, which when multiplied by their level of physical activity or met level $M$ yields their rate of energy expenditure. The rate of energy expenditure can then be related to oxygen consumption, and then $CO_2$ generation via the value of $RQ$. The noted reference provides equations to estimate *BMR* as well as data on met levels for different activities. Assuming RQ equals 0.85, the $CO_2$ generation rate of an individual can be estimated by the following equation:

$$V_{CO2} = BMR\ M\ 0.000484 \tag{4}$$

This updated approach for estimating $CO_2$ generation rates from individuals offers important advantages. First, Equation 3 is based on a 1981 reference that provides no explanation of its basis, while the new approach is derived using established principles of human metabolism and energy expenditure. Also, the new approach characterizes body size using mass rather than surface area, which in practice is estimated and not measured. Body mass is easily measured, and data on body mass distributions for various populations are readily available. The new approach also explicitly accounts for the sex and age of the individuals being considered, which is not the case with Equation 3.

# 3 $CO_2$-BASED VENTILATION METRIC

While a single $CO_2$ concentration metric that characterizes IAQ would be attractive, such a metric is not possible. As discussed earlier, there are many other indoor air contaminants with more significant health and comfort impacts than $CO_2$, and indoor $CO_2$ levels are rarely at concentrations of concern with respect to health effects. Instead, a $CO_2$ metric to evaluate outdoor air ventilation rates on a per person basis relative to a design value or a requirement in a standard is still of value, but it must be based on the space in question and its occupancy. The relevant space information includes the required outdoor air ventilation rate, its geometry (floor area and volume), and the number of occupants and their characteristics that impact the rate at which they generate $CO_2$ (sex, age, body mass and met level). This information can then be used to calculate the expected $CO_2$ concentration at a point in time, and that value can be related to a ventilation metric for a given space. However, performing such a calculation for each space is not realistic for many practitioners and applications. The approach taken in this paper is to perform these calculations using assumptions for the factors affecting $CO_2$ generation rates and ventilation rates. In order to explore these dependencies and how they relate to potential $CO_2$ metric values, indoor $CO_2$ concentrations were calculated for the space types listed in Table 1.

Table 1: Assumptions for $CO_2$ concentration calculations

| | | **Outdoor air ventilation** | | | |
|---|---|---|---|---|---|
| **Space Type** | **Occupant density** (#/100 m$^2$) | **L/s per person** | **h$^{-1}$** | **Occupants** (age, body mass in kg, met level) | **Average $CO_2$ generation per person (L/s)** |
| Classroom (5 to 8 y) | 25 | 7.4 | 2.2 | 12 males (6 y, 23 kg, 2 met); 12 females (6 y, 23 kg, 2 met); 1 male (30 y, 85 kg, 3 met) | 0.0043 |
| Classroom (>9 y) | 35 | 6.7 | 2.8 | 17 males (15 y, 68 kg, 1.7 met); 17 females (15 y, 61 kg, 1.7 met); 1 male (30 y, 85 kg, 2.5 met) | 0.0059 |
| Lecture classroom | 65 | 4.3 | 3.3 | 32 males (20 y, 83 kg, 1.3 met); 32 females (20 y, 71 kg, 1.3 met); 1 male (30 y, 85 kg, 2.5 met) | 0.0046 |
| Restaurant dining room | 70 | 5.1 | 4.3 | 33 males (30 y, 85 kg, 1.5 met); 33 females (30 y, 75 kg, 1.5 met); 2 males (30 y, 85 kg, 2 met); 2 females (30 y, 75 kg, 2 met) | 0.0053 |
| Conference meeting room | 50 | 3.1 | 1.9 | 25 males (30 y, 85 kg, 1.3 met); 25 females (30 y, 75 kg, 1.3 met) | 0.0044 |
| Hotel/motel bedroom | 10 | 5.5 | 0.7 | 5 male (30 y, 85 kg, 1 met); 5 female (30 y, 75 kg, 1 met) | 0.0033 |
| Office space | 5 | 8.5 | 0.5 | 2.5 male (30 y, 85 kg, 1.4 met); 2.5 female (30 y, 75 kg, 1.4 met) | 0.0047 |
| Public assembly/Auditorium | 150 | 2.7 | 4.9 | 75 males (30 y, 85 kg, 1.3 met); 75 females (30 y, 75 kg, 1.3 met) | 0.0044 |
| Public assembly/Lobby | 150 | 2.7 | 4.9 | 75 males (30 y, 85 kg, 2 met); 75 females (30 y, 75 kg, 2 met) | 0.0067 |
| Retail/Sales | 15 | 7.8 | 1.4 | 7.5 male (30 y, 85 kg, 2 met); 7.5 female (30 y, 75 kg, 2 met) | 0.0067 |

Commercial/Institutional space types based on ASHRAE Standard 62.1-2016; outdoor air ventilation based on default occupancy density; ceiling height assumed to equal 3 m.

The space types considered in this analysis were selected from the longer list of commercial/institutional building space types in ASHRAE Standard 62.1 (ASHRAE, 2016a). Future analyses will consider residential buildings covered by Standard 62.2 and other standards (ASHRAE, 2016b), and perhaps other commercial/institutional space types. The second column of Table 1 is the occupant density, expressed as number of people per 100 m$^2$ of floor area (corresponding to the default values in Standard 62.1). The third and fourth columns are the outdoor air ventilation rate in L/s per person and $h^{-1}$ based on Standard 62.1, with the conversion to $h^{-1}$ using a ceiling height of 3 m. The fifth column contains information on the occupants (number, sex, age, body mass and met level) used to calculate their $CO_2$ generation rates, with the average per person generation rate in the last column. Most of the average $CO_2$ generation rates range from 0.004 L/s to 0.005 L/s. Higher values are seen for more active occupants, i.e., Public assembly/Lobby, Retail/Sales spaces and Classrooms (>9 y). A lower value of about 0.003 L/s is seen in the Hotel/motel bedroom spaces where the occupants are assumed to be sleeping, i.e., physical activity levels of 1 met.

For each space type the steady-state $CO_2$ concentration (relative to the outdoor level) and the time required to achieve steady-state were calculated using the assumptions listed in Table 1. These values are presented in the fourth and third columns in Table 2, along with the $CO_2$ concentration that would occur one hour after the space is fully occupied (in the fifth column). Also, a value of $t_{metric}$ is listed for each space type in the second column of the table. This value is the length of time over which the particular space type may be expected to be fully occupied; the $CO_2$ concentration at that time is also listed in the table. These calculations assume all of the occupants enter the space at the same time, which is not necessarily the case in an actual building. The last three columns of the table contain the three $CO_2$ concentration values (steady-state, 1 h after full occupancy and $t_{metric}$) for a ventilation rate that is 25 % below the assumed value in Table 1. These reduced-ventilation cases are considered based on the desire for a $CO_2$-based ventilation metric to be able to capture ventilation deficiencies of this magnitude. The concentration calculations in this table employ the single-zone formulation in Equation 2 and therefore neglect any air and $CO_2$ transport from adjoining spaces. All of the input values used in these calculations can be revised in additional analyses. An online calculator is being developed to allow users to perform these calculations to examine the impact of different inputs.

Table 2: Calculated $CO_2$ concentrations

| | | | **$CO_2$ concentration above outdoors (mg/m$^3$)** | | | **$CO_2$ for 25 % reduced ventilation rate (mg/m$^3$)** | | |
|---|---|---|---|---|---|---|---|---|
| **Space Type** | **$t_{metric}$ (h)** | **Time to steady-state (h)*** | **Steady-state** | **1 h** | **$t_{metric}$** | **Steady-state** | **1 h** | **$t_{metric}$** |
| Classroom (5 to 8 y) | 2 | 1.4 | 1060 | 940 | 1040 | 1410 | 1140 | 1360 |
| Classroom (>9 y) | 2 | 1.1 | 1580 | 1490 | 1580 | 2110 | 1860 | 2080 |
| Lecture classroom | 1 | 0.9 | 1940 | 1870 | 1870 | 2590 | 2370 | 2370 |
| Restaurant | 2 | 0.7 | 1871 | 1850 | 1870 | 2490 | 2390 | 2490 |
| Conference room | 1 | 1.6 | 2526 | 2130 | 2130 | 3370 | 2530 | 2530 |
| Hotel/motel bedroom | 6 | 4.5 | 1080 | 520 | 1060 | 1440 | 560 | 1370 |
| Office space | 2 | 5.9 | 985 | 390 | 630 | 1310 | 420 | 700 |
| Auditorium | 1 | 0.6 | 2900 | 2880 | 2880 | 3870 | 3770 | 3770 |
| Lobby | 1 | 0.6 | 4467 | 4430 | 4430 | 5960 | 5800 | 5800 |
| Retail/Sales | 2 | 2.1 | 1546 | 1170 | 1450 | 2060 | 1340 | 1810 |

* Time to achieve 95 % of steady-state $CO_2$ concentration, i.e., three time constants

The time to reach steady-state in Table 2 is linked to the air change rate in Table 1, i.e., it is three times the inverse of that rate. For most of the spaces, the time to steady-state is less than 1.5 h. In those cases, the three calculated $CO_2$ concentrations are generally within 100 mg/m$^3$, making the timing of a measurement for comparison to a metric less critical than in other spaces. For spaces with longer times required to achieve steady-state, the three calculated $CO_2$ concentrations cover a broader range. For these spaces, the concentration after 1 h of occupancy is more sensitive to the timing of the $CO_2$ measurement than the values at $t_{metric}$ or at steady-state. It is worth noting that the concentrations at $t_{metric}$ (and at steady-state and at 1 h for low time constant cases) tend to cluster around a discrete number of values: 600 mg/m$^3$, 1000 mg/m$^3$, 1500 mg/m$^3$, 2000 mg/m$^3$, 3000 mg/m$^3$ and 4500 mg/m$^3$. Concentrations for other values of the inputs used in these calculations will likely be different, and the ability to identify characteristic concentration values will be reassessed after additional analyses. Of particular note is the Office space, which takes almost 6 h to reach steady-state due in large part to its low occupant density and low air change rate. As a result, the three concentrations values are all quite different. It's unlikely for a typical office space to be at full occupancy for 6 h given lunch schedules; therefore, the $t_{metric}$ value of 2 h and the corresponding concentration of about 600 mg/m$^3$ are more relevant.

Consideration of the last three columns of Table 2 is useful for identifying a time at which the $CO_2$ concentration can be applied as a metric. As seen in this table, the $CO_2$ concentrations at $t_{metric}$ generally exhibit a significant difference between the assumed ventilation rate and the 25 % ventilation deficiency. In cases where the time to reach steady-state is less than 1 h, the concentration at $t_{metric}$ and at 1 h are essentially the same.

Based on the results in Table 2, and the desire to have a $CO_2$ metric that can capture ventilation deficiencies and be less sensitive to the timing of the concentration measurement, Table 3 summarizes potential $CO_2$ metric values for these spaces along with the corresponding measurement time. Given the transient nature of indoor $CO_2$ concentrations and the time to reach steady-state in many cases, it is not surprising that a potential $CO_2$ metric needs to be linked to a concentration measurement time. Therefore, reported $CO_2$ concentrations relative to these and other metrics need to include the time that has passed since the space reached full occupancy. Based on the analysis presented here, the time values are 1 h, 2 h and 6 h. A more complete analysis of other space types with different input values may yield other characteristic times. Future publications will present these additional analyses and an updated consideration of potential metric values.

Table 3: Potential $CO_2$ concentration metrics

| Space Type | $CO_2$ concentration metric, above outdoors (mg/m$^3$) | Corresponding time (h after full occupancy) |
|---|---|---|
| Classroom (5 to 8 y) | 1000 | 2 |
| Classroom (>9 y) | 1500 | 1 |
| Lecture classroom | 2000 | 1 |
| Restaurant dining room | 2000 | 1 |
| Conference meeting room | 2000 | 1 |
| Hotel/motel bedroom | 1000 | 6 |
| Office space | 600 | 2 |
| Public assembly/Auditorium | 3000 | 1 |
| Public assembly/Lobby | 4500 | 1 |
| Retail/Sales | 1500 | 2 |

The use of these concentration-time combinations as metrics of per person ventilation rates requires consideration of occupancy schedules. If the occupancy increases to the assumed full occupancy value over time, which is often the case, but one starts the calculation at the start of any occupancy, then the measured concentration at a given time will be less than the calculated value. Therefore, if the 1 h concentration value is used as a metric, the space could "pass" this criterion even though it would not do so over the long term. However, if the calculation doesn't start until full occupancy exists, then there would be some occupants in place before then, and the measured concentration would be "artificially" higher than it would be if occupancy started all at once. This situation would make the metric conservative, i.e., some spaces might "fail" even though they would pass if the space achieved full occupancy at a single instant in time. Note also that if the early occupants are different from the full occupants (in terms of $CO_2$ generation), it could be problematic.

If the space is not at the occupancy level assumed in Table 1, which could easily be the case for retail or lobby spaces, one could estimate the fraction of the assumed occupancy and reduce the metric in Table 3 accordingly by multiplying by that fractional value. In fact, when applying this metric approach, the actual occupant density must be identified, and the concentration metric adjusted accordingly. It may not be practical to apply these metrics to spaces with particularly transient and short-term occupancies, such as retail and lobbies spaces, which speaks to the need to characterize the space occupancy and schedule as part of any such application.

Application of this $CO_2$ metric approach would require one to report, at a minimum, the following information: space type, occupant density, time at which full occupancy starts, time of $CO_2$ concentration measurement, and measured indoor and outdoor $CO_2$ concentrations. These measurements could then be compared with the values in Table 3, or a subsequent and more comprehensive version, as an indication of whether the ventilation rate per person complies with the value in Standard 62.1 or other ventilation requirement of interest. A more complete application of the approach could involve additional information, including: the ventilation rate per person target value (as an alternative to Standard 62.1), $CO_2$ concentration measurements at 15 min intervals starting at initial occupancy, and information on the ventilation strategy and system operation. As additional analyses are performed and the concept discussed with ventilation and IAQ practitioners and researchers, it is anticipated that the approach will become more well defined.

## 4 CONCLUSIONS

This paper presents an approach to using indoor $CO_2$ concentration measurements as a metric for ventilation rates per person, which accounts for the ventilation requirements and occupancies of specific space types. Calculations of steady-state $CO_2$ concentrations, as well as concentrations at other time intervals, are presented based on space-specific inputs of ventilation rate, space geometry and occupancy. These calculations are used to generate potential $CO_2$ concentration metrics for several space types in commercial/institutional buildings, along with measurement times after full occupancy that need to accompany $CO_2$ concentration measurements that are compared to these metrics. It is clear from these analyses that reported $CO_2$ concentrations for comparison to these, or any other metrics, need to be associated with a measurement time relative to the start of occupancy. Without information on time, such measurements cannot be interpreted.

Note that all of the input values used in these calculations can be revised to examine the impact of other values on the resulting $CO_2$ concentrations. An online calculator is being developed to allow users to perform these additional calculations. In addition, analyses are planned to study the concentrations in residential occupancies. These calculations will consider ventilation requirements from various international standards in single-family homes and multi-family units of different sizes.

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