Development and Application of an Indoor Carbon Dioxide Metric

Running title: Indoor Carbon Dioxide Metric

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ABSTRACT

Indoor carbon dioxide (CO_2) concentrations have been considered for decades in evaluating indoor air quality (IAQ) and ventilation, and more recently in discussions of the risk of airborne infectious disease transmission. However, many of these applications reflect a lack of understanding of the connection between indoor CO_2 levels, ventilation and IAQ. For example, a single indoor concentration such as 1000 ppm_v is often used as a metric of IAQ and ventilation without an understanding of the significance of this or any other value. CO_2 concentrations are of limited value as IAQ metrics, and a single concentration will not serve as a ventilation indicator for spaces with different occupancies and ventilation requirements. An approach has been developed to estimate a space-specific CO_2 level that can serve as a metric of outdoor ventilation rates. The concept is to estimate the CO_2 concentration that would be expected in a specific space given its intended or expected ventilation rate, the number of occupants, the rate at which they generate CO_2 and the time that has transpired since the space was occupied. This paper describes the approach and presents example calculations for several commercial, institutional and residential occupancies.

Practical Implications:

Space-specific CO_2 metrics for ventilation are proposed that account for space geometry, target ventilation rate and occupant characteristics.

These metrics avoid the confusion associated with using a single value for all spaces that ignores important differences between spaces and their occupants.

Application of these metrics provides an opportunity to improve the understanding of the significance of indoor CO_2 concentrations by practitioners and other building professionals.

KEYWORDS

carbon dioxide; indoor air quality; metrics; occupancy; standards; ventilation

INTRODUCTION

Indoor air quality (IAQ) is characterized by the chemical and physical constituents of air that impact occupant health, comfort and productivity as well as the durability of building materials, furnishings and equipment. The number of airborne contaminants in most indoor environments is quite large, and the impacts on occupants are known for only a limited number of contaminants. The large number of contaminants and their wide variation among and within buildings makes it extremely challenging to quantify IAQ, let alone to distinguish between good and bad IAQ based on a single metric. There have been efforts to define IAQ metrics, but none have been shown to fully capture the multiple health and comfort impacts of IAQ very well or have become widely accepted [1-3], though recent discussions, analyses and proposals reflect progress [4-9].

Many discussions of IAQ metrics have included indoor CO_2 concentrations. In fact, indoor CO_2 has been featured in discussions of ventilation and IAQ since the 18th century, when Lavoisier suggested that CO_2 build-up rather than oxygen depletion was responsible for “bad air” indoors [10]. About one hundred years later, von Pettenkofer suggested that biological contaminants from human occupants caused indoor air problems, not CO_2, though he proposed using CO_2 as an indicator of vitiated air. Since that time, discussions of CO_2 in relation to IAQ and ventilation have evolved, focusing on the impacts of CO_2 on building occupants, how CO_2 relates to occupant perception of bioeffluents, the use of indoor CO_2 as a tracer gas to estimate ventilation rates, and the control of outdoor air ventilation rates based on measured CO_2 concentrations [11-13].

Indoor CO_2 concentrations are typically well below values of interest based on health concerns and relative to workplace concentration limits, e.g., the OSHA limit of 5,000 ppm_v averaged over any 8-hour work shift during a 40-hour work week [14]. Several studies have shown associations of CO_2 levels above about 1000 ppm_v with self-reported sick building syndrome symptoms, absenteeism and performance [15-17], but these studies did not control for other contaminants and environmental conditions. Therefore these associations are likely due to lower ventilation rates elevating CO_2 concentrations as well as the concentrations of other more important indoor contaminants [18,19]. More recent work has examined the impacts of pure CO_2 at concentrations in the range of those commonly observed in non-industrial environments [18,20,21]. Some but not all of these studies have seen associations between CO_2 and reductions in cognitive performance. More research is needed to understand these inconsistent results and to explore potential mechanisms.

Indoor CO_2 concentrations are related to the outdoor air ventilation rates per person specified in standards, guidelines and building regulations [22-24] based on the relationship of indoor CO_2 to bioeffluent emissions from building occupants. These outdoor air requirements reflect research dating back to the 1930s on the amount of ventilation needed to control the perception of odor associated with these bioeffluents [25]. This research found that about 7.5 L/s to 9 L/s per person of ventilation air dilutes body odor to levels judged to be acceptable by individuals entering a space from 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. These studies showed that CO_2 concentrations about 700 ppm_v above outdoors resulted in roughly 80 % of unadapted visitors judging the odor to be acceptable. For an outdoor CO_2 level of 300 ppm_v, this concentration difference corresponds roughly to the commonly-cited indoor value of 1000 ppm_v. (Note that outdoor levels have increased to over 400 ppm_v since these odor acceptability studies were done [26].) This body of research supports 1000 ppm_v of CO_2 as a reflection of body odor acceptability as perceived by unadapted visitors to a building. However, there are many other important indoor air contaminants that are not associated with the number of occupants, and CO_2 concentrations are not good indicators of those contaminants as noted below.[13]

Indoor CO_2 concentrations are being increasingly discussed as an indicator of the risk of airborne infectious disease transmission [27,28]. In that context, CO_2 can be useful as an indicator of ventilation rates as discussed in this paper, but that first requires the determination of ventilation rates that are protective against these risks. Alternatively, CO_2 can be employed as a more direct indicator of infection risk using concepts such as rebreathed air [29,30]. These applications of CO_2 are the topic of current research, which will hopefully provide useful insights that can be implemented in practice. However, it is important to note that the fate and transport of infectious aerosols is different from that of CO_2 in several important ways, including the fact that CO_2 does not deposit on surfaces and is not removed by particle filtration and other air cleaning technologies [31].

Indoor CO_2 concentrations have been widely promoted and applied as a metric of IAQ and ventilation for decades, in many cases without a clear explanation of what they are intended to characterize or the limitations in such applications [32]. Many practitioners use 1000 ppm_v as an IAQ metric, in many cases erroneously basing it on ASHRAE Standard 62.1 [23]. However, that standard has not contained an indoor CO_2 limit for almost 30 years [25,33]. While a CO_2 concentration metric that characterizes IAQ would be attractive, there are many other indoor air contaminants with more significant health and comfort impacts than CO_2, and many of those contaminants have been shown not to be well-correlated with indoor CO_2 concentrations [34-36]. However, a CO_2 metric to evaluate outdoor air ventilation rates is feasible, but it must be based on the space in question and its occupancy.

This paper proposes using CO_2 as an indicator or metric of outdoor air ventilation rates relative to a design value, a recommended ventilation rate or a requirement in a standard. 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. For indoor CO_2 to serve as a meaningful indicator of ventilation, all of these factors need to be considered. This paper describes calculations to predict the expected CO_2 concentration at a specific time, which can be compared to a measured concentration as an indication that the actual ventilation rate is below the assumed or desired ventilation rate. Example calculations demonstrating this concept are presented and discussed for several commercial, institutional and residential occupancies, which are necessarily based on multiple assumptions about these spaces and their occupants. In order to facilitate these calculations for other values of these inputs, an online tool *QICO2* has been developed and is described briefly in the Discussion section of this paper.

THEORY AND BACKGROUND

This section presents the well-established single-zone mass balance theory on which the CO_2 metric for ventilation presented in this paper is based. It then describes how to estimate CO_2 generation rates of building occupants, as these values are needed to implement this CO_2 metric. The ventilation requirements in ASHRAE Standards 62.1 and 62.2 are then described, as they serve as the basis for the example calculations described later.

Single-zone mass balance

The underlying model on which the CO_2 metric for ventilation is based is a single-zone mass balance of a ventilated space. While a single-zone mass balance is a simplification and will not apply in all buildings and spaces, it is widely used when considering indoor air contaminants and is helpful in this application. A single-zone mass balance of CO_2 in a building or space of interest can be expressed as follows:

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

where V is the volume of the building or space being considered (m^3), C is the CO_2 concentration in the space (ppm_v), C_{out} is the outdoor CO_2 concentration, t is time (h), Q is the volumetric flow of outdoor air into the building (space) from outdoors and from the building (space) to the outdoors (L/s), and G is the CO_2 generation rate in the space (L/s). For the purposes of this discussion, the outdoor air ventilation rate Q refers to the total rate at which outdoor air enters the building or space of interest, including mechanical and natural ventilation as well as infiltration. Note that the relative proportions of mechanical ventilation, natural ventilation and infiltration depend on the specific building, its ventilation system design and operation, and the weather conditions._Note that, in general, Q, C_{out} and G are functions of time, as noted in the equation, but they are assumed to be constant in this discussion. Also, air density differences between indoors and outdoors 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 indoor removal of CO_2, concentration differences between building zones, and CO_2 transport between zones. These last two assumptions are not always valid, and their appropriateness must be considered in applying single-zone, mass balance analysis to CO_2 or any other indoor contaminant.

Based on these assumptions, the solution to Equation 1 can be expressed as follows:

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

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. A constant value of G requires that the occupancy and the intensity of occupant activity remain constant, but in many spaces occupancy will be too short or too variable for steady-state to be achieved. However, as noted above, G is assumed to be constant in these calculations. 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, at which point the concentration (relative to outdoors) will be 95 % of its steady-state value. 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. Assuming steady-state has been achieved, Equation 2 can be solved for C_{ss} as follows:

$$C_{SS} = C_{out} + {}^{G}/_{Q}, \qquad (3)$$

If G and Q are both expressed in L/s, the value on the right side of the equation is multiplied by 10^6 to express C_{ss} in units of ppm_v.

CO_2 generation from building occupants

An approach to estimating CO_2 generation rates from building occupants based on human metabolism and exercise physiology concepts has been described [37]. This approach uses the basal metabolic rate *BMR*, 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 yields their rate of energy expenditure. The rate of energy expenditure can be related to oxygen consumption, and then the CO_2 generation rate via the value of the respiratory quotient *RQ*. *RQ* is the ratio of the volumetric rate at which CO_2 is produced to the rate at which oxygen is consumed and depends primarily on diet. Reference 37 provides a discussion of *RQ* values, equations to estimate *BMR* and data on met levels for different activities. Assuming *RQ* equals 0.85, the CO_2 generation rate of an individual can be estimated with the following equation:

$$V_{CO2} = BMR\ M\left({}^{T}\!/_{P}\right)\ 0.000179 \tag{4}$$

where V_{CO2} is the CO_2 generation rate per person (L/s), M is the level of physical activity, sometimes referred to as the metabolic rate or met level (dimensionless), T is the air temperature (K), and P is the air pressure (kPa). There have been a small number of recent studies in which measured CO_2 generation rates from humans have been compared with predictions based on Equation 4. The level of agreement between measurements and predictions is variable, but it should be noted that the predictions are highly dependent on the assumed value of M and that the sample sizes in these studies tend to be small [38,39]. All of the CO_2 generation rates in this paper are based on an air temperature of 296.15 K (23 °C).

Ventilation requirements in standards

In order to use the CO_2 metric approach described in this paper, the user must have a target ventilation rate for the space they are considering. That rate can come from a ventilation standard or some other reference, but it serves as the basis for comparing measured CO_2 concentrations to the CO_2 metric value derived using this approach. The calculations that follow use ventilation rates based on ANSI/ASHRAE Standard 62.1 and Standard 62.2, which apply to non-residential and residential buildings respectively [22,23].

ASHRAE Standard 62.1 contains minimum outdoor air ventilation requirements in the prescriptive Ventilation Rate Procedure in the form of a People Outdoor Air Rate R_p (L/s•person) and an Area Outdoor Air Rate R_a (L/s•m^2) for 109 different Occupancy Categories [23]. Those two values are combined to yield the outdoor air requirement to the breathing zone V_{bz} of the space using the following equation:

$$V_{bz} = R_p \times P_z + R_a \times A_z \tag{5}$$

where P_z is the number of people in the zone and A_z is the net occupiable floor area of the zone. For example, in the case of Office Space, $R_p = 2.5$ L/s•person and $R_a = 0.3$ L/s•m^2. For an office with a floor area of 100 m^2 and an occupancy of 5 individuals, the outdoor air requirement under Standard 62.1 is 8.5 L/s•person. The standard requires that the breathing zone outdoor airflow be adjusted to account for air distribution in the space to determine the required zone outdoor airflow. These zone outdoor airflows are then used to determine the outdoor air intake required at the air handler, with adjustments for multiple-zone recirculating systems and occupancy variations over time (referred to as diversity in the standard). However, adjustments for zone air distribution, multiple-zone system effects and occupant diversity are not considered here.

ASHRAE Standard 62.2 applies to residential occupancies and contains an outdoor air ventilation requirement for a dwelling unit expressed by the following equation [22]:

$$Q_{tot} = 0.15A_{floor} + 3.5(N_{br} + 1), \qquad (6)$$

where Q_{tot} is the total required ventilation rate in L/s, A_{floor} is the floor area in m^2 and N_{br} is the number of bedrooms. For example, in a house with a floor area of 200 m^2 and 3 bedrooms, the ventilation requirement is 44 L/s. The value of Q_{tot} is used in this analysis without any of the adjustments allowed by Standard 62.2, such as a credit for infiltration.

Other ventilation standards, regulations and guidance documents have been published around the world. Many of these ventilation requirements were first issued in the 1980s and 1990s, in some cases in the form of mandatory standards and building regulations, and in other cases less formal guidance [40,41]. European Committee for Standardization (CEN) standard EN 16798-1 describes methods for determining ventilation requirements for non-residential and residential buildings, with default criteria contained in an informative appendix [24]. Method 3 in that standard provides minimum ventilation airflow rates in L/s per person “estimated to meet requirements for both perceived air quality and health in the occupied zone” for four categories of indoor environmental quality related to the level of occupant expectations. Those categories are I-high level of expectation, II-medium level, III-moderate level, and IV-low level. As noted in that standard, "A normal level would be "Medium". A higher level may be selected for occupants with special needs (children, elderly, persons with disabilities, etc.). A lower level will not provide any health risk but may decrease comfort." The ventilation rates for offices provided in the informative appendix are 20 L/s, 14 L/s, 8 L/s and 5.5 L/s per person for categories I, II, III and IV respectively.

The adequacy of the minimum outdoor air ventilation requirements in ASHRAE and other standards has been debated for decades and those discussions continue. However, these requirements are taken as a given in this discussion, but these calculations of a CO_2 metric for ventilation can be performed for any ventilation rate.

CO_2-BASED VENTILATION METRIC

While a single CO_2 concentration metric that comprehensively characterized IAQ would be attractive, indoor CO_2 concentrations only reflect occupant exposure to contaminant sources that are proportional to the number of occupants in a space and their activity levels. However, a CO_2 metric can be used to evaluate outdoor air ventilation rates relative to a design value, a recommended rate or a requirement in a standard, but such a CO_2 ventilation metric must be based on the space in question and its occupancy. Relevant space information includes the required outdoor air ventilation rate, geometry (floor area and ceiling height), 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). The concept behind this ventilation metric approach is to calculate an expected CO_2 concentration for a space under consideration and then to compare that value to a measured CO_2 concentration. A measured value that is above the expected or metric value serves as an indication that the space is not being ventilated at the assumed rate. This section presents calculations for the proposed CO_2-based ventilation metric for several commercial-institutional and residential buildings and discusses how the results can support its application.

CO_2 Metric Example Calculations for Commercial-Institutional Buildings

In order to demonstrate and explore this approach to a CO_2 ventilation metric, indoor CO_2 concentrations were calculated using Equation (2) for the space types listed in Table 1, which includes several commercial-institutional building spaces covered by ASHRAE Standard 62.1 [23].

The space types considered in these examples were selected from the commercial-institutional building space types listed in ASHRAE Standard 62.1. The second column of Table 1 is the occupant density, expressed as the 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 for all spaces except for those identified in the note to the table. The fifth column contains information on the occupants (number, sex, age, body mass and met level) used to calculate the CO_2 generation rates, with the average per person generation rate in the last column. In some cases the number of occupants of a particular type is listed as an integer value plus one-half in order for the total number to match the Standard 62.1 default occupant density. Most of the average CO_2 generation rates range from about 0.004 L/s to 0.006 L/s per person. Higher values are seen in spaces where the occupants are assumed to be more active, i.e., Lobby and Retail/Sales. The average CO_2 generation rate in the hotel bedroom is below 0.004 L/s given that the occupants are assumed to be sleeping. The assumptions reflected in Table 1 are not claimed to be representative but rather to provide example results for the purpose of these discussions.

For each space type the time required to achieve steady-state and the steady-state CO_2 concentration (above the outdoor concentration) were calculated using the assumptions in Table

1. These values are presented in the third and fourth 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). A value of t_{metric} is listed for each space type in the second column of the table, which is the length of time over which the particular space type may be expected to be fully occupied. The values of t_{metric} are provided for the purposes of discussion and are not suggested to be definitive or recommended for these particular space types. The CO_2 concentration at t_{metric} is listed in the sixth column of the table. Note that for some spaces, the CO_2 concentration will not have achieved steady-state at this time. In these spaces the occupancy is not expected to be constant long enough for a steady-state concentration to occur, so the concentration at t_{metric} is offered as a more realistic metric. 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 CO_2 removal and any air and CO_2 transport from adjoining spaces. They also assume that all of the occupants enter the space at the same time, which will not necessarily be the case in an actual building.

The time for the CO_2 concentration (relative to outdoors) to reach 95 % of 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 ppm_v, making the timing of a measurement for comparison to a metric less critical than in spaces with longer time constants. For spaces with longer times required to achieve steady-state, the three calculated CO_2 concentrations cover a broader range, and the concentration after 1 h of occupancy is more sensitive to time than the values at t_{metric} or at steady-state. Of particular note is the Office space, which takes almost 6 h to reach steady-state due in large part to its low air change rate. As a result, the three concentrations values are quite different, covering a range of almost 3 to 1. However, it's unlikely for a typical office space to be at full occupancy for 6 h given lunch schedules and other variations in scheduling; therefore, the t_{metric} value of 2 h and the corresponding concentration of about 383 ppm_v above outdoors is presumably more relevant in practice.

It is worth noting that the concentrations at t_{metric} (and at steady-state and 1 h for low time constant cases) tend to cluster around a number of values: 400 ppm_v, 600 ppm_v, 1100 ppm_v, 1500 ppm_v, and 2500 ppm_v above C_{out}. Calculated concentrations for other input values will be different, and the ability to identify characteristic concentrations would need to be reassessed after additional analyses. Nevertheless, 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 amount of time required to reach steady-state, 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. Note that for the Office space, the CO_2 concentrations at t_{metric} for the Standard 62.1 ventilation rate and the 25 % reduced rate are within 50 ppm_v due to the long time constant of that space. This small difference, relative to typical measurement uncertainties, makes it difficult to identify a potential concentration metric that will capture ventilation rate deficiencies in offices. Additional analyses over a range of input values and for other space types are needed to convert these potential metric values to values that are more well-justified for application in practice.

Table 4 presents calculated CO_2 concentrations for the same commercial-institutional space types shown in Tables 2 and 3 using 10 L/s per person instead of the Standard 62.1 ventilation requirements. This value has been discussed in the context of airborne infectious disease control and is therefore of current interest [42-45]. Compared to the Standard 62.1 calculations, the outdoor air ventilation rates in units of h^{-1} are much higher for 10 L/s per person and the times to steady-state are much lower, except in the office space for which the Standard 62.1 ventilation requirement is already 8.5 L/s per person. For several spaces, the outdoor air ventilation rates in units of h^{-1} are two or more times the Standard 62.1 value, with a corresponding decrease in the time to steady-state and the calculated CO_2 concentrations. Note that there is much less variation in the calculated CO_2 concentrations among the different spaces and for the different calculation times. In contrast to the CO_2 concentrations in Table 2 for the Standard 62.1 rates, all but one of these values are less than 900 ppm_v above outdoors; in several spaces, the Standard 62.1 concentrations are well above 1000 ppm_v above outdoors. Table 4 also contains calculated CO_2 concentrations for a 25 % reduction in ventilation rates, which corresponds to 7.5 L/s per person. As in the case of the Standard 62.1 requirements, the CO_2 concentrations in the Office space at t_{metric} are similar for the baseline 10 L/s per person ventilation rate and the 25 % reduced rate due to the long time constant of that space, making it difficult to identify a potential metric that will capture ventilation rate deficiencies of this magnitude. Based on consideration of the calculated CO_2 concentrations in the different space types and the impact of a 25 % reduction in the ventilation rate, potential concentration metrics are provided in Table 5. In considering the impact of 10 L/s per person on CO_2 concentration, it is important to bear in mind that an increase of this magnitude may not be achievable in all buildings and ventilation systems given the details of their existing designs. Such increases may also be challenging in some cases depending on outdoor contaminant and humidity levels and the system's capacity to manage these loads.

CO_2 Metric Example Calculations for Residential Buildings

This section presents example calculations of the CO_2 ventilation metric in residential spaces, which can exhibit large variations in dwelling and family size and in occupant characteristics, as well as potentially less predictable durations of occupancy relative to some commercial-institutional spaces. However, the many hours associated with sleep provide helpful options for these analyses in bedrooms. Equation (2) is again be used to calculate CO_2 concentrations for a given space based on the assumed CO_2 generation and ventilation rates. Several residential occupancies were considered as listed in Table 6, which describes three families: a baseline with 4 members (2 adults and 2 children), a larger family with 2 additional children, and a smaller family with 2 adults and no children. The sex, age, body mass and level of physical activity are described for each family member, including the CO_2 generation rate for each person as well as the average generation rate per person for all of the defined occupants. These generation rates are assumed to exist for the whole house during non-sleeping hours when occupants are assumed to be more active, and for individual bedrooms when occupants are sleeping. For each occupancy in Table 6, CO_2 concentrations were calculated for the ventilation scenarios listed below:

Whole house:

- Ventilation rate requirement from ASHRAE Standard 62.2
- Ventilation rate of 0.5 h^{-1}

Bedrooms:

- 62.2/Perfect Distribution: Bedroom ventilation rate is the Standard 62.2 rate divided by the number of house occupants, multiplied by the number of bedroom occupants
- 62.2/Uniform Distribution: Bedroom ventilation rate is the Standard 62.2 rate divided by the whole house floor area, multiplied by the bedroom floor area
- 0.5/Perfect Distribution: Bedroom ventilation rate is 0.5 h^{-1} times the house volume divided by the number of house occupants and then multiplied by the number of occupants in each bedroom
- 0.5/Uniform Distribution: Bedroom ventilation rate is 0.5 h^{-1} times the house volume divided by the whole house floor area, and then multiplied by the bedroom floor area
- 10 L/s per person/Perfect Distribution: Bedroom ventilation rate is 10 L/s multiplied by the number of bedroom occupants

The whole house calculations are done using the ventilation requirements based on ASHRAE Standard 62.2 as well for 0.5 h-1, a value contained in residential ventilation standards in several Nordic countries [46] and which has been shown to reduce health symptoms in residential buildings [47,48]. For the bedroom cases, two idealized air distribution scenarios are applied to the Standard 62.2 and 0.5 h^{-1} whole house rates. In the first, Perfect Distribution, the whole house rate is divided by the number of occupants in the house. That normalized value is multipled by the number of occupants in each bedroom to determine the outdoor air ventilation provided to each bedroom. Perfect Distibution may correspond to a ventlation system that supplies outdoor air directly to each bedroom based on the number of occupants. Under Uniform Distribution, the whole house rate is divided by the floor area of the house. That normalized value is multipled by the floor area of each bedroom to determine the outdoor air ventilation provided to each bedroom. Uniform distribution may correspond to a building ventilated by infiltration only, an exhaust-only ventilation system or a mechanical ventilation system that is integrated into a forced-air distribution system. Both of these distribution cases are idealized, but they are included to account for the potential impacts of air distribution.The last bedroom ventilation rate, 10 L/s per person/Perfect Distribution, assumes 10 L/s of outdoor air is supplied for each person in each bedroom and is based on the CEN residential ventilation recommendation [24]. As noted for the commercial-institutional buildings, the assumptions used in the residential calculations are not claimed to be representative but rather to provide example results for the purpose of these discussions.

Table 7 presents the assumed dimensions (ceiling heights and floor areas) for the houses and bedrooms considered, and Table 8 presents ventilation information and calculated CO_2 concentrations for each case. The second and third columns of Table 8 contain the outdoor air ventilation rate in L/s per person and h^{-1} for the whole house and bedroom cases. The fourth column is the time to reach 95 % of the steady-state CO_2 concentration (relative to outdoors). The whole house air change rates based on Standard 62.2 are about 0.3 h^{-1} in all but the small house/baseline family case, where it is just over 0.4 h^{-1}. The bedroom air change rates cover a range of almost 10 to 1 for the different cases in the large house/baseline family and the small house/small family. In these two cases, delivering the whole house ventilation rate of 0.5 h^{-1} directly to the bedrooms under Perfect Distribution results in ventilation rates above 15 L/s per person. On the other hand, Uniform Distribution to the bedrooms results in less than 5 L/s per person in several cases. These air change rates impact the time required to achieve steady-state, which are 6 h or less for the bedrooms cases other than for 62.2/Uniform. For the whole house, the time to 95 % of steady-state is always 6 h for the 0.5 h^{-1} cases and ranges from about 7 h to 11 h for the 62.2 cases.

As was the case for the commercial-institutional spaces, the residential calculations presented in Table 8 were redone with the assumed ventilation rates reduced by 25 %. These results are shown in Table SI.1. CO_2 concentrations that increase by 100 ppm_v or more relative to the corresponding values in Table 8 are noted in bold font in Table SI.1. The whole-house, reduced-ventilation concentrations at t_{metric} increase very little relative to the corresponding values in Table 8, by about 40 ppm_v or less, which is less than the measurement accuracy of many field measurements of CO_2 concentrations. This lack of increase is partly due to the long time constants of the whole-house cases, which allow little time for the concentration to increase after only 2 h. The increases in the bedroom concentrations at t_{metric} are larger for the reduced ventilation cases, typically at least 50 ppm_v and often several hundred ppm_v. These larger increases for the bedroom support the use of a 6 h value of t_{metric} to capture ventilation deficiencies. In contrast to the commercial-institutional occupancies discussed earlier, residential cases may be more likely to vary in space size, occupancy and ventilation, making it difficult to generalize the calculated CO_2 concentrations. Therefore potential CO_2 concentration metrics, like those presented for the commercial-institutional spaces, are not provided for the residential cases. Instead, the specific house, occupancy and air distribution approach of interest need to be accounted for in developing a metric value for evaluating the adequacy of the ventilation rate.

DISCUSSION

The CO_2 values calculated as described in this paper can be applied to a specific space by comparing them to measured values, with a measured value that is higher serving as an indication that the actual ventilation rate is below the assumed or desired ventilation rate. Whether one uses a CO_2 metric value for one of the specific examples in this paper, the potential metrics values shown in Table 3 and 5, or a preferably a value calculated for the specific space being considered, it is critical that the user carefully assess and report the inputs used to calculate the CO_2 metric. These inputs include the space geometry, target ventilation rate of the space, occupancy of the space of over time, time of the CO_2 measurement, and information on the occupants used to estimate the CO_2 generation rate.

Using the CO_2 concentration at a specific time as a metric of ventilation requires consideration of occupancy schedules. If the concentration calculation starts as soon as the space contains any occupants (but the actual occupancy increases from unoccupied to the assumed full occupancy over time), the calculated concentration at a given time will be less than it would have been than if the space was fully occupied all at once. Therefore, if the 1 h or t_{metric} concentration value is used as a metric, the space CO_2 concentration could be below this criterion even though it would not be the case over the longer term. However, if the concentration calculation is delayed until the space is fully occupied, then the actual concentration increase will have a “head start” on that calculation and may exceed the metric value. This situation would make the metric conservative, i.e., some spaces might “fail” (i.e., indicate a lower ventilation rate than desired) even though they would pass if the space achieved full occupancy at a single instant in time. Note also that if early occupants are different from the full occupants (in terms of their CO_2 generation rates), it could complicate application of this approach.

Residential cases are more likely to vary in space size, occupancy and ventilation than many commercial-institutional occupancies, making it difficult to offer generalizations about calculated CO_2 concentrations. Rather than offering potential CO_2 concentration metrics, like those presented in Tables 3 and 5 for the commercial-institutional spaces, the house, occupancy and air distribution approach for the case of interest need to be accounted for in developing a metric value for evaluating the adequacy of the ventilation rate. For comparisons with a calculated whole house value, the measured CO_2 concentration should be a volume-weighted, whole house average based on the concentrations measured in each room. Since the calculations assume constant occupancy, the measurement needs to occur after a sufficiently longer period of constant occupancy, which can be challenging in some residences. Ideally, a constant occupancy period that lasts for t_{metric} occurs for the building or space being considered, and the calculated metric value can then provide a more meaningful indicator of ventilation.

In the case of bedrooms, the calculated CO_2 concentrations can be compared to measured values in the bedroom. Given the more stable bedroom occupancy during sleeping, that comparison should occur several hours after the bedroom is occupied for sleeping. A value of t_{metric} for bedrooms of 6 h is offered for making these comparisons. A measured CO_2 concentration that is higher serves as an indication that the actual ventilation rate is below the assumed or desired ventilation rate. Note that these comparisons neglect the impact of interzone transport on the bedroom CO_2 concentration, which will be impacted by factors such as operation of central HVAC systems, open bedroom doors, and transfer grilles in doors and other interior partitions. Also, the calculation assumes that the CO_2 concentration starts at the outdoor level.

However, the initial concentration in the bedroom may be higher than outdoors due to previous occupancy of the house, in which case the calculated concentration will be lower than it would if the actual initial concentration were considered. This situation would result in the calculated metric value being conservative, meaning some spaces might “fail” that would have otherwise “passed” if they started at the outdoor CO_2 concentration.

There are several limitations to the approach described in this paper. First, the examples provided are for very specific spaces. The assumed input values are based on reasonable judgements, but different values could be justified. In actual application, some of these inputs may be hard to identify, for example occupant characteristics (e.g., age and body mass). Also, this approach assumes that the ventilation rate, outdoor CO_2 concentration and the rate of CO_2 generation by the occupants are all constant, which won’t necessarily be the case. While the user needs to examine the validity of these assumptions, additional analyses will allow the estimation of the uncertainty associated with specific levels of variation in these parameters. As noted in this paper, this approach can be particularly challenging to apply in spaces with more transient occupancies, such as retail spaces and lobbies. Also, spaces with long time constants, i.e., low air change rates, such as some offices will create challenges in that the CO_2 concentration will not necessarily increase significantly relative to measurement uncertainty during periods of constant occupancy.

While the potential CO_2 concentrations metrics shown in Tables 3 and 5 are attractive for general application, they are presented only for illustrative purposes. Additional analyses are needed before these specific CO_2 metrics values should be widely applied. Also, a more complete application of the approach would involve additional information, such as continuous CO_2 concentration measurements starting at initial occupancy and information on ventilation system operation, including the operating schedule and outdoor air intake rates as a function of time. A simplified approach may also merit consideration, in which one only considers the measured CO_2 concentration and the elapsed time since the start of occupancy. Additional analyzes of additional scenarios and input values are needed to explore this simplified concept. In addition to the analysis of more space types and a wider range of input values, this approach would benefit from application by practitioners in order to gauge its practicality and to identify other issues regarding its usefulness as a ventilation metric. Field studies in which calculated metric values are studied in conjunction with measured outdoor air intake rates would be useful and likely lead to improvements in the approach.

As noted earlier in this paper, an online tool *QICO2* has been developed to implement the calculation methodology presented here, allowing users to vary the required input values to examine other cases[49], and is available at https://pages.nist.gov/CONTAM-apps/webapps/CO2Tool/#/. After providing the relevant inputs, or selecting from a number of predefined cases, the tool allows the user to estimate indoor CO_2 concentrations in a ventilated space at steady-state, 1 h after occupancy and at a selected value of t_{metric}. The predefined cases include all of the example calculations described in this paper. The tool allows the user to modify the inputs contained in these examples or to create new cases, and for a given case to compare the calculated CO_2 concentrations for two different ventilation rates.

CONCLUSION

While indoor CO_2 is not a comprehensive indicator of IAQ, this paper proposes using CO_2 as an indicator or metric of outdoor air ventilation rates. This ventilation metric concept reflects the fact that indoor CO_2 concentrations depend 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. As a result, the value of the metric necessarily will be different for different spaces, as opposed to using a single value for all spaces and occupancies as has been widely suggested. If all of these factors are properly accounted for, indoor CO_2 concentrations can serve as meaningful indicators of ventilation. Example calculations are presented that provide insight into the application of this concept and demonstrate its potential merit, but more analysis is needed for a wide range of space types, occupancy scenarios and target ventilation rates. An online tool that has been developed that will facilitate the application of the CO_2-based ventilation metric, enabling more meaningful interpretations of measured indoor CO_2 concentrations. 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 and useful.

REFERENCES

1. Jackson MC, Penn RL, Aldred JR, Zeliger HI, Cude GE, Neace LM, Kuhs JF, Corsi RL. Comparison Of Metrics For Characterizing The Quality Of Indoor Air. presented at: 12th International Conference on Indoor Air Quality and Climate; 2011; Austin, Texas.
2. Hollick HH, Sangiovanni JJ. A Proposed Indoor Air Quality Metric for Estimation of the Combined Effects of Gaseous Contaminants on Human Health and Comfort. In: Nagda NL, ed. *Air Quality and Comfort in Airliner Cabins, ASTM STP 1393*. American Society for Testing and Materials; 2000:76-98.
3. Moschandreas D, Yoon S, Demirev D. Validation of the Indoor Environmental Index and Its Ability to Assess In-Office Air Quality. *Indoor Air*. 2005;15 (11):874-877.
4. Wargocki P, Wei W, Bendžalová J, Espigares-Correa C, Gerard C, Greslou O, Rivallain M, Sesana MM, Olesen BW, Zirngibl J, Mandin C. TAIL, a new scheme for rating indoor environmental quality in offices and hotels undergoing deep energy renovation (EU ALDREN project). *Energy and Buildings*. 2021;244

5. Logue JM, Price PN, Sherman MH, Singer BC. A Method to estimate chronic health impact of air pollutants in U.S. Residences. *Environmental Health Perspectives*. 2012;120:216-222.
6. Teichman K, Howard-Reed C, Persily A, Emmerich S. *Characterizing Indoor Air Quality Performance Using a Graphical Approach*. National Institute of Standards and Technology. 2015. NIST Technical Note 1868.
7. AIVC. Workshop - Is ventilation the answer to indoor air quality control in buildings? Do we need performance-based approaches? Brussels. Air Infiltration and Ventilation Centre; 2017. https://www.aivc.org/resources/collection-papers/volume/march-14-15-2017-ventilation-answer-indoor-air-quality-control
8. Cony Renaud Salis L, Abadie M, Wargocki P, Rode C. Towards the definition of indicators for assessment of indoor air quality and energy performance in low-energy residential buildings. *Energy and Buildings*. 2017;152:492-502.
9. Jones B. Metrics of Health Risks from Indoor Air. *REHVA Journal*. 2017;June
10. Klauss AK, Tull RH, Roots LM, Pfafflin JR. History of the Changing Concepts in Ventilation Requirements. *ASHRAE Journal*. 1970;12(June):51-55.
11. ASTM. D6245-2018, Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation. 2018. West Conshohocken, PA, ASTM International.
12. Emmerich SJ, Persily AK. *State-of-the-Art Review of* CO_2 *Demand Controlled Ventilation Technology and Application*. National Institute of Standards and Technology. 2001. NISTIR 6729.
13. ASHRAE. *Position Document on Indoor Carbon Dioxide*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2022.

14. OSHA. Air Contaminants. 2017. Occupational Safety & Health Adminisitration, U.S. Department of Labor. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1000.
15. Apte MG, Fisk WJ, Daisey JM. Associations Between Indoor CO2 Concentrations and Sick Building Syndrome Symptoms in US Office Buildings: An Analysis of the 1994-1996 BASE Study Data. *Indoor Air*. 2000;10 (4):246-257.
16. Shendell DG, Prill R, Fisk WJ, Apte MG, Blake D, Faulkner D. Associations Between Classroom CO_2 Concentrations and Student Attendance in Washington and Idaho. *Indoor Air*. 2004;14 (5):333-341.
17. Gaihre S, Semple S, Miller J, Fielding S, Turner S. Classroom Carbon Dioxide Concentration, School Attendance, and Educational Attainment. *Journal of School Health*. 2014;84(9):569-574.
18. Lowther SD, Dimitroulopoulou S, Foxall K, Shrubsole C, Cheek E, Gadeberg B, Sepai O. Low Level Carbon Dioxide Indoors—A Pollution Indicator or a Pollutant? A Health-Based Perspective. *Environments*. 2021;8(11)
19. Wargocki P. What we know and should know about ventilation. *REHVA Journal*. 2021;58 (2):5-13.
20. Du B, Tandoc MC, Mack ML, Siegel JA. Indoor CO2 concentrations and cognitive function: A critical review. *Indoor Air*. Nov 2020;30(6):1067-1082.
21. Fisk W, Wargocki P, Zhang X. Do Indoor CO2 Levels Directly Affect Perceived Air Quality, Health, or Work Performance. *ASHRAE Journal*. 2019;61 (9):70-77.
22. ASHRAE. *ANSI/ASHRAE Standard 62.2-2019, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA. 2019.

23. ASHRAE. *ANSI/ASHRAE Standard 62.1-2019, Ventilation for Acceptable Indoor Air Quality*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA. 2019.
24. CEN. *Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. European Committee for Standardization. 2019. EN 16798-1:2019.
25. Persily A. Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. *Building and Environment*. 2015;91:61-69.
26. NOAA. *Trends in Atmospheric Carbon Dioxide Levels*. National Oceanic and Atmospheric Administration, Earth Systems Research Laboratory. 2018. https://www.esrl.noaa.gov/gmd/ccgg/.
27. Peng Z, Jimenez JL. Exhaled CO2 as a COVID-19 Infection Risk Proxy for Different Indoor Environments and Activities. *Environmental Science & Technology Letters*. 2021;8(5):392-397.
28. EMG/SPI-B. *Application of CO2 monitoring as an approach to managing ventilation to mitigate SARS-CoV-2 transmission*. UK Scientific Advisory Group of Emergenices, Environmental Modelling Group (EMG) and Scientific Pandemic Insights Group on Behaviours (SPI-B). 2021.
29. Rudnick SN, Milton DK. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air*. 2003;13 (3):237-245.
30. Bueno de Mesquita PJ, Delp WW, Chan WR, Bahnfleth WP, Singer BC. Control of airborne infectious disease in buildings: Evidence and research priorities. *Indoor Air*. Nov 24 2021;

31. Kappelt N, Russel HS, Kwiatkowski S, Afshari A, Johnson MS. Correlation of Respiratory Aerosols and Metabolic Carbon Dioxide. *Sustainabilty*. 2021;Online 5 November 2021
32. Persily AK. Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide. *ASHRAE Transactions*. 1997;103 (2):193-204.
33. Persily AK. Don’t Blame Standard 62.1 for 1000 ppm CO2. *ASHRAE Journal*. 2021;63(2):74-75.
34. Ramalho O, Wyart G, Mandin C, Blondeau P, Cabanes P-A, Leclerc N, Mullot J-U, Boulanger G, Redaelli M. Association of carbon dioxide with indoor air pollutants and exceedance of health guideline values. *Building and Environment*. 2015;93:115-124.
35. Derbez M, Berthineau B, Cochet V, Lethrosne M, Pignon C, Riberon J, Kirchner S. Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Building and Environment*. 2014;72:173-187.
36. Justo Alonso M, Wolf S, Jørgensen RB, Madsen H, Mathisen HM. A methodology for the selection of pollutants for ensuring good indoor air quality using the de-trended cross-correlation function. *Building and Environment*. 2022;209
37. Persily AK, de Jonge L. Carbon Dioxide Generation Rates of Building Occupants. *Indoor Air*. 2017;27(5):868-879.
38. Yang L, Wang X, Li M, Zhou X, Liu S, Zhang H, Arens E, Zhai Y. Carbon dioxide generation rates of different age and gender under various activity levels. *Building and Environment*. 2020;186
39. Fan X, Sakamoto M, Shao H, Kuga K, Ito K, Lan L, Wargocki P. Emission rate of carbon dioxide while sleeping. *Indoor Air*. Aug 1 2021;

40. Limb MJ. *A Review of International Ventilation, Airtightness, Thermal Insulation and Indoor Air Quality Criteria*. Air Infiltration and Ventilation Centre, Coventry, Great Britain. 2001. TN 55.
41. Dimitroulopoulou C, Bartzis J. Ventilation rates in European office buildings: A review. *Indoor and Built Environment*. 2014;23(1):5-25.
42. WHO. *Roadmap to improve and ensure good indoor ventilation in the context of COVID-19*. World Health Organization. 2021.
43. REHVA. *REHVA COVID 19 Guidance*. Federation of European Heating, Ventilation and Air Conditioning Associations. 2021.
44. Li Y, Cheng P, Jia W. Poor ventilation worsens short-range airborne transmission of respiratory infection. *Indoor Air*. 2021;Accepted 12 October 2021
45. EMG. *Role of Ventilation in Conotrolling SARS-CoV-2 Transmission*. UK Scientific Advisory Group of Emergenices. 2020.
46. Bekö G, Lund T, Nors F, Toftum J, Clausen G. Ventilationratesinthebedroomsof500Danishchildren. *Building and Environment*. 2010;45:2289-2295.
47. Sundell J, Levin H, Nararoff WW, Cain WS, Fisk WJ, Grimsrud DT, Gyntelberg F, Li Y, Persily AK, Pickering AC, Samet JM, Spengler JD, Taylor ST, Weschler CJ. Ventilation Rates and Health: Multidisciplinary Review of the Scientific Literature. *Indoor Air*. 2011;21 (3):191-204.
48. Wargocki P, Sundell J, Bischof W, Brundrett G, Fanger PO, Gyntelberg F, Hanssen SO, Harrison P, Pickering A, Seppanen O, Wouters P. Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN). *Indoor Air*. 2002;12 (2):113-128.

49. Persily A, Polidoro BJ. *Indoor Carbon Dioxide Metric Analysis Tool*. National Institute of Standards and Technology. 2022. NIST Technical Note 2213.

Table 1: CO_2 concentration calculations for commercial-institutional building

Space Type	**Occupant density** (#/100 m^2)	**Outdoor air ventilation**		**Occupants** (age in y, body mass in kg, physical activity in met)	**Average CO_2 generation per person** (L/s)
		L/s per person	h^{-1}		
Classroom (5 to 8 y)	25	7.4	2.2	12 males (8, 23, 2); 12 females (8, 23, 2); 1 male (35, 85, 3)	0.0047
Classroom (>9 y)	35	6.7	2.8	17 males (15, 65, 1.7); 17 females (15, 60, 1.7); 1 male (35, 85, 2.5)	0.0063
Lecture classroom	65	4.3	2.5	32 males (20, 80, 1.3); 32 females (20, 70, 1.3); 1 female (35, 75, 2)	0.0049
Lecture hall (fixed seats)	150	4.0	4.3	74.5 males (20, 80, 1.3); 74.5 females (20, 70, 1.3); 1 female (35, 75, 2)	0.0049
Restaurant dining room	70	5.1	3.2	33 males (35, 85, 1.5); 33 females (35, 75, 1.5); 2 males (35, 85, 3); 2 females (35, 75, 3)	0.0058
Conference meeting room	50	3.1	1.9	25 males (35, 85, 1.4); 25 females (35, 75, 1.4)	0.0051
Hotel/motel bedroom	10	5.5	0.7	1 male (35, 85, 1.0); 1 female (35, 75, 1.0)	0.0036
Office space	5	8.5	0.5	2.5 male (35, 85, 1.4); 2.5 female (35, 75, 1.4)	0.0051
Auditorium	150	2.7	1.9	75 males (35, 85, 1.3); 75 females (35, 75, 1.3)	0.0047
Lobby	150	2.7	2.9	75 males (35, 85, 2); 75 females (35, 75, 2)	0.0073
Retail/Sales	15	7.8	1.1	7.5 male (35, 85, 2); 7.5 female (35, 75, 2)	0.0091

Occupancy densities and outdoor air ventilation requirements from ASHRAE Standard 62.1-2019; ceiling height assumed to equal 3 m except as follows: Lecture classroom 4 m; Lecture hall with fixed seats 5 m, Restaurant dining room 4 m, Auditorium 7.5 m, Lobby 5 m, and Retail/Sales 4 m.

Table 2: Calculated CO_2 concentrations for commercial-institutional buildings using ASHRAE Standard 62.1 ventilation requirements

			CO_2 concentration above outdoors (ppm_v)			**CO_2 for 25 % reduced ventilation rate** (ppm_v)		
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	631	563	624	842	682	811
Classroom (>9 y)	1	1.1	937	881	881	1250	1099	1009
Lecture classroom	1	1.2	1154	1058	1058	1538	1301	1301
Lecture hall (fixed seats)	1	0.7	1226	1210	1210	1634	1570	1570
Restaurant dining room	1	0.9	1133	1087	1087	1511	1374	1374
Conference/meeting room	1	1.6	1642	1386	1386	2189	1646	1646
Hotel/motel bedroom	6	4.5	661	319	648	881	344	836
Office space	2	5.9	599	239	383	798	254	427
Auditorium	1	1.5	1750	1500	1500	2333	1790	1790
Lobby	1	1.0	2692	2547	2547	3590	3187	3187
Retail/Sales	2	2.9	1165	759	1023	1553	848	1233

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

Table 3: Potential CO_2 concentration metrics based on ASHRAE 62.1 ventilation requirements

Space Type	**CO_2 concentration metric above outdoors (ppm_v)**	**Corresponding time (h after full occupancy)**
Classroom (5 to 8 y)	600	2
Classroom (>9 y)	900	1
Lecture classroom	1100	1
Lecture hall (fixed seats)	1200	1
Restaurant dining room	1100	1
Conference meeting room	1400	1
Hotel/motel bedroom	600	6
Office space	400	2
Auditorium	1500	1
Lobby	2500	1
Retail/Sales	1000	2

Table 4: Calculated CO_2 concentrations for commercial-institutional buildings for an outdoor air ventilation rate of 10 L/s per person

			CO_2 concentration above outdoors (ppm_v)			**CO_2 for 25 % reduced ventilation rate** (ppm_v)		
Space Type	**Outdoor ventilation rate** (h^{-1})	**Time to steady-state (h)***	**Steady -state**	**1 h**	**t_{metric}**	**Steady -state**	**1 h**	**t_{metric}**
Classroom (5 to 8 y)	3.0	1.0	467	444	466	623	557	616
Classroom (>9 y)	4.2	0.7	629	620	620	839	803	803
Lecture classroom	5.9	0.5	492	490	490	656	647	647
Lecture hall (fixed seats)	10.8	0.3	490	490	490	654	654	654
Restaurant dining room	6.3	0.5	576	575	575	768	762	762
Conference/meeting	6.0	0.5	509	508	508	678	671	671
Hotel/motel bedroom	1.2	2.5	363	254	363	485	288	482
Office space	0.6	5.0	509	230	356	678	246	403
Auditorium	7.2	0.4	473	472	472	630	627	627
Lobby	10.8	0.3	727	727	727	969	969	969
Retail/Sales	1.4	2.2	909	673	848	1212	771	1052

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

Table 5: Potential CO_2 concentration metrics based on 10 L/s of outdoor air per person

Space Type	**CO_2 concentration metric above outdoors** (ppm$_v$)	**Corresponding time** (h after full occupancy)
Classroom (5 to 8 y)	450	2
Classroom (>9 y)	600	1
Lecture classroom	500	1
Lecture hall (fixed seats)	500	1
Restaurant dining room	600	1
Conference meeting room	500	1
Hotel/motel bedroom	350	6
Office space	350	2
Auditorium	500	1
Lobby	700	1
Retail/Sales	850	2

Table 6: Occupancy assumptions for residential CO_2 calculations

Case	**Occupants** (age in y, body mass in kg, physical activity in met)	**CO_2 generation per person** (L/s)	**Average CO_2 generation per person** (L/s)
Baseline family of 4			
Whole house	1 male (40, 85, 1.3); 1 female (40, 75, 1.3); 1 male (6, 23, 2); 1 female (10, 40, 1.7)	0.0053 0.0042 0.0045 0.0046	0.0046
Primary Bedroom	1 male (40, 85, 1); 1 female (40, 75, 1)	0.0041 0.0032	0.0036
Child Bedrooms	1 male (6, 23, 1); 1 female (10, 40, 1)	0.0023 0.0027	0.0025
Additional occupants in larger family of 6			
Whole house	1 male (8, 32, 2); 1 female (4, 14, 2)	0.0054 0.0034	0.0046*
Primary Bedroom	No change		0.0036
Child Bedrooms	1 male (8, 32, 1); 1 female (4, 14, 1)	0.0027 0.0017	0.0023*
Smaller family of 2 (no children)			
Whole house	Only adults		0.0047
Primary Bedroom	Only adults		0.0036

* Average CO_2 generation rate accounts for all 6 occupants in whole house and all 4 children in child bedrooms.

Table 7: House and bedroom sizes for cases considered

	Ceiling height (m)	**House floor area (m^2)**	**Primary bedroom floor area (m^2)**	**Child bedrooms floor area (m^2)**
Large House	2.74	250	30	20
Small house	2.44	100	20	15

Table 8: Ventilation rates and calculated CO_2 concentrations for the residential cases

	Outdoor air ventilation		**Time to 95 % of steady-state** (h)	**CO_2 Concentration above outdoors** (ppm_v)		
Case*	L/s per person	h^{-1}		**Steady-state**	**1 h**	**t_{metric} ****
Large House/Baseline family						
Whole house – 62.2	12.9	0.27	11.1	360	85	151
Whole house – 0.5 h^{-1}	23.8	0.50	6.0	195	77	123
62.2/PBR/Perfect	12.9	1.13	2.7	282	191	282
62.2/CBR/Perfect	12.9	0.85	3.5	193	110	191
62.2/PBR/Uniform	3.1	0.27	11.1	1176	279	944
62.2/CBR/Uniform	4.1	0.27	11.1	602	143	483
0.5 h^{-1}/PBR/Perfect	23.8	2.08	1.4	153	134	153
0.5 h^{-1}/CBR/Perfect	23.8	1.56	1.9	104	82	104
0.5 h^{-1}/PBR/Uniform	5.7	0.50	6.0	637	251	605
0.5 h^{-1}/CBR/Uniform	7.6	0.50	6.0	326	128	310
10 L/s per person/PBR/Perfect	10.0	0.88	3.4	363	212	362
10 L/s per person/CBR/Perfect	10.0	0.66	4.6	248	119	243
Large House/Large family						
Whole house – 62.2	9.8	0.31	9.8	468	124	215
Whole house – 0.5 h^{-1}	15.9	0.50	6.0	288	113	182
62.2/PBR/Perfect	9.8	0.85	3.5	373	214	371
62.2/CBR/Perfect	9.8	0.64	4.7	240	114	235
62.2/PBR/Uniform	3.5	0.31	9.8	1036	274	872
62.2/ CBR/Uniform	4.7	0.31	9.8	500	132	421
0.5 h^{-1}/PBR/Perfect	15.9	1.39	2.2	229	172	229
0.5 h^{-1}/CBR/Perfect	15.9	1.04	2.9	148	96	147
0.5 h^{-1}/PBR/Uniform	5.7	0.50	6.0	637	251	605
0.5 h^{-1}/ CBR/Uniform	7.6	0.50	6.0	308	121	292
10 L/s per person/PBR/Perfect	10.0	0.88	3.4	363	212	362
10 L/s per person/CBR/Perfect	10.0	0.66	4.6	234	113	230
Small House/Baseline family						
Whole house – 62.2	7.3	0.43	7.0	640	223	368
Whole house – 0.5 h^{-1}	8.5	0.50	6.0	548	216	346
62.2/PBR/Perfect	7.3	1.07	2.8	501	329	501
62.2/CBR/Perfect	7.3	0.71	4.2	342	174	337
62.2/PBR/Uniform	2.9	0.43	7.0	1253	436	1157
62.2/ CBR/Uniform	4.4	0.43	7.0	570	199	527
0.5 h^{-1}/PBR/Perfect	8.5	1.25	2.4	429	306	429
0.5 h^{-1}/CBR/Perfect	8.5	0.83	3.6	293	166	291
0.5 h^{-1}/PBR/Uniform	3.4	0.50	6.0	1073	422	1019
0.5 h^{-1}/CBR/Uniform	5.1	0.50	6.0	488	192	464
10 L/s per person/PBR/Perfect	10.0	1.48	2.0	363	280	363
10 L/s per person/CBR/Perfect	10.0	0.98	3.1	248	155	247
Small House/Small family						
Whole house – 62.2	11.0	0.32	9.2	430	119	205
Whole house – 0.5 h^{-1}	16.9	0.50	6.0	279	110	176
62.2/PBR/Perfect	11.0	1.62	1.8	330	265	330
62.2/PBR/Uniform	2.2	0.32	9.2	1652	458	1417
0.5 h^{-1}/PBR/Perfect	16.9	2.50	1.2	215	197	215
0.5 h^{-1}/PBR/Uniform	3.4	0.50	6.0	1073	422	1019
10 L/s per person/PBR/Perfect	10.0	1.45	2.0	363	280	363

* PBR and CBR stand for Primary bedroom and Child bedroom, respectively.

** t_{metric} equals 2 h for the whole house and 6 h for the bedrooms.

SUPPLEMENTARY INFORMATION

Table SI.1: Calculated CO_2 concentrations for residential cases with 25 % ventilation rate reduction

	Outdoor air ventilation		**Time to 95 % of steady-state** (h)	**CO_2 Concentration above outdoors** (ppm$_v$)		
Case*	L/s per person	h^{-1}		**Steady-state**	**1 h**	**t_{metric} ****
Large House/Baseline family						
Whole house – 62.2	9.7	0.20	14.8	**481**	88	160
Whole house – 0.5 h^{-1}	17.8	0.38	8.0	260	81	137
62.2/PBR/Perfect	9.7	0.85	3.5	376	215	374
62.2/CBR/Perfect	9.7	0.63	4.7	257	121	251
62.2/PBR/Uniform	2.3	0.20	14.8	**1568**	288	**1104**
62.2/CBR/Uniform	3.1	0.20	14.8	**803**	147	565
0.5 h^{-1}/PBR/Perfect	17.8	1.56	1.9	204	161	204
0.5 h^{-1}/CBR/Perfect	17.8	1.17	2.6	139	96	139
0.5 h^{-1}/PBR/Uniform	4.3	0.38	8.0	**849**	265	**760**
0.5 h^{-1}/ CBR/Uniform	5.7	0.38	8.0	**435**	136	389
10 L/s per person/PBR/Perfect	7.5	0.66	4.6	**485**	233	**475**
10 L/s per person/CBR/Perfect	7.5	0.49	6.1	331	129	314
Large House/Large family						
Whole house – 62.2	7.3	0.23	13.0	**624**	129	231
Whole house – 0.5 h^{-1}	11.9	0.38	8.0	384	120	202
62.2/ PBR/Perfect	7.3	0.64	4.7	**497**	235	**486**
62.2/ CBR/Perfect	7.3	0.48	6.2	320	122	302
62.2/PBR/Uniform	2.6	0.23	13.0	**1381**	284	**1035**
62.2/CBR/Uniform	3.5	0.23	13.0	**667**	137	500
0.5 h^{-1}/PBR/Perfect	11.9	1.04	2.9	306	198	305
0.5 h^{-1}/CBR/Perfect	11.9	0.78	3.8	197	107	195
0.5 h^{-1}/PBR/Uniform	4.3	0.38	8.0	**849**	265	**760**
0.5 h^{-1}/ CBR/Uniform	5.7	0.38	8.0	**410**	128	367
10 L/s per person/PBR/Perfect	7.5	0.66	4.6	**485**	233	**475**
10 L/s per person/CBR/Perfect	7.5	0.49	6.1	312	121	296
Small House/Baseline family						
Whole house – 62.2	4.5	0.32	9.9	**853**	234	404
Whole house – 0.5 h^{-1}	6.4	0.38	8.0	**730**	228	385
62.2/ PBR/Perfect	5.4	0.80	3.7	**668**	369	**663**
62.2/ CBR/Perfect	5.4	0.53	5.6	**456**	189	**438**
62.2/PBR/Uniform	2.2	0.32	9.3	**1671**	459	**1427**
62.2/ CBR/Uniform	3.3	0.32	9.3	**760**	209	**650**
0.5 h^{-1}/PBR/Perfect	6.4	0.94	3.2	**572**	348	**570**
0.5 h^{-1}/CBR/Perfect	6.4	0.63	4.8	**390**	181	381
0.5 h^{-1}/PBR/Uniform	2.5	0.38	8.0	**1430**	447	**1279**
0.5 h^{-1}/ CBR/Uniform	3.8	0.38	8.0	**651**	203	**582**
10 L/s per person/PBR/Perfect	7.5	1.11	2.7	**485**	324	**484**
10 L/s per person/CBR/Perfect	7.5	0.74	4.1	331	173	327
Small House/Small family						
Whole house – 62.2	8.3	0.24	12.3	**573**	124	221
Whole house – 0.5 h^{-1}	12.7	0.38	8.0	372	116	196
62.2/ PBR/Perfect	8.3	1.22	2.5	**441**	310	**440**
62.2/PBR/Uniform	1.7	0.24	12.3	**2203**	476	**1692**
0.5 h^{-1}/PBR/Perfect	12.7	1.88	1.6	286	242	286
0.5 h^{-1}/PBR/Uniform	2.5	0.38	8.0	**1430**	447	**1279**
10 L/s per person/PBR/Perfect	7.5	1.11	2.7	**485**	324	**484**

* PBR and CBR stand for Primary bedroom and Child bedroom, respectively.

** t_{metric} equals 2 h for the whole house and 6 h for the bedrooms.