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# Development and Application of an Indoor Carbon Dioxide Metric

Andrew Persily*, Brian Polidoro

National Institute of Standards and Technology, Gaithersburg, USA

**Corresponding email: andyp@nist.gov*

**SUMMARY**

Indoor carbon dioxide ($CO_2$) concentrations have been used for decades to evaluate indoor air quality (IAQ) and ventilation. However, many of these applications reflect a lack of understanding of the connection between indoor $CO_2$, ventilation rates and IAQ. After many unsuccessful efforts to dissuade practitioners and researchers from using $CO_2$ as a ventilation and IAQ metric, an approach has been developed to estimate $CO_2$ concentrations to serve as indicators of outdoor air ventilation rates per person, though not overall IAQ. Rather than a single concentration for all spaces and occupancies, a space-specific $CO_2$ metric of ventilation is proposed that is based primarily on recommended or required ventilation rates per person and occupant characteristics. This paper describes the approach, with sample calculations discussed for several commercial, institutional and residential building occupancies. An online calculator to perform these calculations is also described.

**KEYWORDS**

*carbon dioxide; indoor air quality; metrics; ventilation*

## 1 INTRODUCTION

Indoor air quality (IAQ) is characterized by the presence and concentrations of chemical and physical substances in air that impact occupant health, comfort and productivity. The number of airborne contaminants in most indoor environments is large, and their impacts on building occupants are known for only a limited number of substances. The wide variation in contaminants among and within buildings and over time 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 health and comfort impacts of IAQ nor have any been accepted in the field (Jackson et al., 2011; Hollick and Sangiovanni, 2000; Moschandreas et al., 2005; Teichman et al. 2015).

For many years, some have promoted indoor $CO_2$ concentrations as a metric of IAQ and ventilation, in many cases without a clear explanation of the application and associated limitations (Persily 1997). Nevertheless, practitioners and researchers frequently use 1800 mg/m$^3$ (roughly 1000 ppm$_v$) as a metric, often erroneously basing it on ASHRAE Standard 62.1 (ASHRAE 2019a). However, that standard has not contained an indoor $CO_2$ limit for almost 30 years (Persily 2015). There have been many papers and presentations that have attempted to clarify the significance of indoor $CO_2$ concentrations, with some advocating that they not be used in IAQ and ventilation evaluations. However, calls to stop poorly informed applications of indoor $CO_2$ are not succeeding. While efforts to educate designers, practitioners and others need to continue, this paper presents an approach for using indoor

$CO_2$ concentrations as a metric of ventilation rate per person that considers the space-specific parameters that determine indoor $CO_2$ levels and describes an on-line calculator to estimate indoor $CO_2$ concentrations for use with this approach (Persily, 2018; Persily and Polidoro, 2019). Note that these $CO_2$ concentrations are not intended as an overall IAQ metric, but only to evaluate per person ventilation rates.

Indoor $CO_2$ concentrations can be linked to the outdoor air ventilation rates per person specified in standards, guidelines and building regulations (ASHRAE, 2019a; ASHRAE, 2019b; CEN, 2007b; CEN, 2009). These requirements reflect research on the amount of ventilation needed to control the perception of odors associated with the byproducts of human metabolism, as well as other contaminants emitted by materials and furnishings (Persily 2015). This research shows that about 7.5 L/s to 9 L/s per person of outdoor air dilutes body odor to levels judged to be acceptable by individuals entering a room, i.e., unadapted visitors. This research also supports a steady-state $CO_2$ concentration of 1800 mg/m$^3$ as a reflection of body odor acceptability perceived by unadapted visitors in these studies. 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.

## 2 $CO_2$-BASED VENTILATION METRIC

While a $CO_2$ concentration metric that characterizes IAQ would be attractive, such a metric is not possible, in part because there are many indoor air contaminants with significant health and comfort impacts and whose concentrations are unrelated to $CO_2$ concentrations. Previous work describes the use of $CO_2$ as an indicator or metric of outdoor air ventilation rates per person (Persily, 2018; Persily and Polidoro, 2019). As discussed in those papers, indoor $CO_2$ concentrations depend primarily on the rate $G$ at which occupants generate $CO_2$, the outdoor air ventilation rate of the space, the time since occupancy began, and the outdoor $CO_2$ concentration. Note that outdoor air ventilation refers to the total rate at which outdoor air enters a building or space, including mechanical and natural ventilation as well as infiltration. The cited papers describe the single-zone mass balance theory for calculating indoor $CO_2$ concentrations, noting that the indoor concentration will only achieve steady-state if conditions, specifically ventilation rate and $G$ are constant for a long enough period of time. Those papers stress the assumptions on which the single-zone mass balance is based, including that the concentration in the space can be characterized by a single value, which some describe as the well-mixed assumption. Also, a constant $G$ requires that occupancy and activity remain constant, but in many spaces both will be too short or too variable for steady-state to occur. A convenient means of assessing whether steady-state is likely to be achieved is by comparing the duration of constant occupancy to the time constant of the space. The time constant is the inverse of the outdoor air change rate; under constant occupancy and activity the indoor concentration will be about 95 % of steady-state after three time constants.

### 2.1 Commercial and Institutional Buildings

In the previous work on this $CO_2$ metric concept (Persily 2018), several space types were selected from the commercial/institutional building space types or "Occupancy Categories" in Table 6-1 of ASHRAE Standard 62.1 (ASHRAE 2019a). For these spaces, as shown in Table 1, $CO_2$ concentrations above outdoors were calculated at steady-state, after 1 h of occupancy, and at a time $t_{metric}$, which was selected as a time over which the particular space type may be expected to be fully occupied based on the judgement of the authors. The assumed occupant densities, occupant characteristics and $CO_2$ generation rates are described in (Persily 2018).

Table 1. Calculated $CO_2$ concentrations in commercial and institutional occupancies

| Space type | $t_{metric}$ (h) | Time to steady-state (h)* | $CO_2$ concentration above outdoors, mg/m$^3$** Steady-state | 1 h | $t_{metric}$ |
|---|---|---|---|---|---|
| Classroom (5 to 8 y) | 2 | 1.4 | 1060 | 940 | 1040 |
| Classroom (>9 y) | 2 | 1.1 | 1580 | 1490 | 1580 |
| Lecture classroom | 1 | 0.9 | 1940 | 1870 | 1870 |
| Restaurant | 2 | 0.7 | 1871 | 1850 | 1870 |
| Conference room | 1 | 1.6 | 2526 | 2130 | 2130 |
| Hotel/motel bedroom | 6 | 4.5 | 1080 | 520 | 1060 |
| Office space | 2 | 5.9 | 985 | 390 | 630 |
| Auditorium | 1 | 0.6 | 2900 | 2880 | 2880 |
| Lobby | 1 | 0.6 | 4467 | 4430 | 4430 |
| Retail/Sales | 2 | 2.1 | 146 | 1170 | 1450 |

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

** To convert these concentrations too ppm$_v$, divide these values by 1.8.

For most of the spaces, the time to steady-state is less than 1.5 h. In those cases, the three calculated concentrations are generally within 100 mg/m$^3$, making measurement timing for comparison to a metric less critical, though they still need to take place about an hour after occupancy starts. For spaces with longer times to steady-state, the three $CO_2$ concentrations cover a broader range. For those spaces, the $CO_2$ concentration after 1 h will be more sensitive to the timing of the measurement than the $t_{metric}$ or steady-state values. The office space 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 are quite different. It's unlikely for many office spaces to be at full occupancy for 6 h given lunch schedules and other common events; therefore, the $t_{metric}$ value of 2 h and the corresponding concentration of about 600 mg/m$^3$ are more relevant. These same calculations are presented in Persily (2018) for ventilation rates 25 % lower than those assumed here, given the desire for a $CO_2$-based ventilation metric to be able to capture situations in which ventilation rates are lower than intended. Based on this previous work, including the desire for a $CO_2$ metric to identify ventilation deficiencies and to be less sensitive to the timing of the concentration measurement, Table 2 contains potential $CO_2$ metric values for these spaces along with the corresponding measurement time. Reported $CO_2$ concentrations relative to these and any other metrics need to include the time that has passed since the space reached full occupancy. Consideration of additional spaces and different input values would possibly yield other potential metrics.

Table 2. Potential $CO_2$ concentration metrics

| Space type | $CO_2$ concentration metric, above outdoors mg/m$^3$ (µL/L*) | Corresponding time, h after full occupancy |
|---|---|---|
| Classroom (5 to 8 y) | 1000 (550) | 2 |
| Classroom (>9 y) | 1500 (850) | 2 |
| Lecture classroom | 2000 (1100) | 1 |
| Restaurant | 2000 (1100) | 2 |
| Conference room | 2000 (1100) | 1 |
| Hotel/motel bedroom | 1000 (550) | 6 |
| Office space | 600 (350) | 2 |
| Auditorium | 3000 (1700) | 1 |
| Lobby | 4500 (2500) | 1 |
| Retail/Sales | 1500 (850) | 2 |

* µL/L is equivalent to ppm$_v$; values in parentheses are approximate conversions

## 2.2 Residential Buildings

Extending this approach to residential spaces is challenging given the wide variations in dwelling and family size and in occupant characteristics, as well as the often unpredictable durations of occupancy relative to many commercial and institutional spaces. However, the hours associated with sleep provide longer periods of constant occupancy to support analyses in bedrooms. The approach for residential buildings in Persily and Polidoro (2019) is to again to use single zone, steady-state mass balance analysis to calculate the $CO_2$ concentrations for a given space based on assumptions about $CO_2$ generation rate and ventilation rate. In order to explore these dependencies for residential spaces, indoor $CO_2$ concentrations were calculated for 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 used to calculate the $CO_2$ generation rate for each person during non-sleep hours when occupants are assumed to be more active, and when occupants are sleeping.

For each occupancy, $CO_2$ concentrations were calculated for several different ventilation scenarios. Whole house concentrations were calculated using rates based on ASHRAE Standard 62.2 and a fixed rate of 0.5 $h^{-1}$. Bedroom concentrations were calculated based on Standards 62.2, 0.5 $h^{-1}$ and 10 L/s per person. For the bedroom cases, two idealized outdoor 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 then multipled by the number of occupants in each bedroom to determine the ventilation 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. In the other case, Uniform Distribution, the total ventilation rate is normalized by the floor area of the entire house, and the ventilation rate of each bedroom is that normalized rate multiplied by its floor area. 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. For the case with bedroom ventilation rates of 10 L/s per person, 10 L/s of outdoor air is supplied for each person in each bedroom, with that rate based on recommendations in CEN (2007a) and (2009).

Persily (2019) presents calculated $CO_2$ concentrations for these different residential occupancies and ventilation scenarios. In contrast to the commercial and institutional occupancies discussed earlier, the variation in space size, occupancy and ventilation in these residential cases makes it difficult to generalize these results. Instead, the house, occupancy and air distribution approach all need to be accounted for in developing a metric or reference point for evaluating the adequacy of the outdoor air ventilation rate relative to a target value. The online tool discussed in the next section was developed to implement these concepts.

# 3 ON-LINE $CO_2$ METRIC CALCULATOR

In order to support application of the proposed $CO_2$ concentration metric concept, an online tool (https://pages.nist.gov/CONTAM-apps/webapps/CO2Tool/#/) has been developed. This 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 $t_{metric}$. These calculated concentrations can then be compared with measured concentrations to evaluate whether the intended or required ventilation rate is actually being achieved. Such a building-specific metric or reference value is far better than using a single value for all indoor spaces, such as 1800 mg/m$^3$.

When using the tool, the user first selects whether they wish to analyze a commercial/institutional building or a residential building and then enters the required inputs. For commercial/institutional buildings, the tool allows one to select from several of the commercial and institutional space types listed in ASHRAE Standard 62.1-2019, and to use the default values in that standard for outdoor ventilation requirements and occupant density. The tool makes assumptions about the occupants in each space, i.e., sex, body mass, age and activity level in met, needed to calculate the $CO_2$ generation rate in the space. However, all of these inputs can be modified by the user. For residential buildings, the user selects a whole building or bedroom analysis. If whole building, the user can use of a ventilation requirement based on Standard 62.2-2019 or enter a whole building air change rate in $h^{-1}$. If instead they are performing a bedroom analysis, they need to select a whole building ventilation requirement, e.g. using Standard 62.2, or enter a L/s per person ventilation rate. In either case, they also need to define the air distribution as Perfect or Uniform as described above. For both commercial/institutional or residential buildings, an Alternate ventilation rate can be input to compare the results to those obtained with a Primary ventilation rate.

Once the user has completed the inputs, a Results screen summarizes the inputs and displays a plot of the indoor $CO_2$ concentration versus time, along with concentration values at steady-state, $t_{metric}$ and 1 h after occupancy for the Primary and Alternate ventilation rates. The tool is applied by comparing the calculated $CO_2$ concentrations 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. Since the calculation assumes constant occupancy, the measurement needs to occur while occupancy is constant, which can be limited in duration. Ideally, a constant occupancy period that lasts for $t_{metric}$ occurs for the building or space under consideration, and the calculated value at that time is then used for the comparison. If constant occupancy does not last that long, the $t_{metric}$ value in the calculator can be modified.

For bedrooms, the calculated $CO_2$ concentrations are also intended to be compared to measured values. Given the fairly stable bedroom occupancy during sleeping, that comparison should occur several hours after the bedroom is occupied for sleeping. The tool has a default value of $t_{metric}$ for bedrooms of 6 h. A measured value that is higher than the calculated is an indication that the actual ventilation rate is below the assumed or desired rate. Note that this comparison neglects the impact of interzone $CO_2$ transport on the bedroom concentration.

## 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 spaces. Application of this approach requires one to report information on the space being considered and its occupancy, the time at which full occupancy starts, time of $CO_2$ concentration measurement, and the measured indoor and outdoor $CO_2$ concentrations. These measurements can then be compared with the values calculated with the online tool as an indication of whether the ventilation rate complies with the value in Standard 62.1, Standard 62.2 or another ventilation requirement of interest. As additional analyses are performed and the concept is discussed with practitioners and researchers, it is anticipated that the approach will evolve and become more well-defined and useful. An online calculator has been developed to allow users to exercise this approach. Based on user feedback, the calculator will be revised in the future. One specific addition being considered is to enable Monte Carlo analyses to quantify the impact of uncertainties in the input values on the calculated $CO_2$ concentrations, as well as to identify the most important input values, using the methodology described in Jones et al. (2015).

Note that there are several important limitations with this approach. Most importantly, it only provides a metric of ventilation rates per person; it will not characterize overall IAQ or the concentrations of other indoor air contaminants that impact occupant health, comfort and productivity. Also, it has only been applied to a limited number of cases. Additional analyses with this approach are needed to better understand its application and usefulness for different building types and occupants. The single-zone analysis approach does not account for air distribution impacts on spatial variations in $CO_2$ concentrations nor does it account for transient effects associated with changes in occupant activities.

**7 REFERENCES**


ASHRAE. 2019a. ANSI/ASHRAE Standard 62.1-2019 Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

ASHRAE. 2019b. 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.

CEN. 2007a. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, Brussels, European Committee for Standardization.

CEN. 2007b. Ventilation for buildings - Energy performance of buildings - Guidelines for inspection of ventilation systems, Brussels, European Committee for Standardization.

CEN. 2009. Ventilation for buildings - Determining performance criteria for residential ventilation systems, Brussels, European Committee for Standardization.

Hollick HH and Sangiovanni JJ. 2000. 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, West Conshohocken, PA, American Society for Testing and Materials, 76-98.

Jackson MC, Penn RL, Aldred JR, Zeliger HI, Cude GE, Neace LM, Kuhs JF and Corsi RL. 2011. Comparison Of Metrics For Characterizing The Quality Of Indoor Air, *12th International Conference on Indoor Air Quality and Climate*, Austin, Texas.

Jones B, Das P, Chalabi Z, Davies M, Hamilton I, Lowe R, Mavrogianni A, Robinson D, and Taylor J. 2015. Assessing uncertainty in housing stock infiltration rates and associated heat loss: English and UK case studies. Building and Environment, 92, 644-656.

Moschandreas D, Yoon,S and Demirev D. 2005. Validation of the Indoor Environmental Index and Its Ability to Assess In-Office Air Quality. *Indoor Air*, 15 (11), 874-877.

Persily AK. 1997. Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide. *ASHRAE* Transactions, 103 (2), 193-204.

Persily A. 2015. Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. Building and Environment, 91, 61-69.

Persily A. 2018. Development of an Indoor Carbon Dioxide Metric, 39th AIVC Conference, Antibes Juan-les-Pins, France, 791-800.

Persily A, and Polidoro B. 2019. Residential Application of an Indoor Carbon Dioxide Metric, 40th AIVC Conference, Ghent, Belgium, 995-1007.

Teichman K, Howard-Reed,C, Persily A and Emmerich S. 2015. Characterizing Indoor Air Quality Performance Using a Graphical Approach, National Institutte of Standards and Technology.