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Measurement and Control of Ventilation Rates in Commercial Buildings in California

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Measurement and Control of Ventilation Rates in Commercial Buildings in California is the final report for the Measurement and Control of Ventilation Rates in Commercial Buildings in California project (contract number PIR-14-003) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Ventilation of buildings with outdoor air is necessary to maintain acceptable indoor air quality and health conditions. California's Title 24 Standards specify minimum ventilation rates for buildings. The purpose of this project was to advance the science and technology needed to better control minimum outdoor air ventilation rates in existing and new commercial buildings in California. The project team performed several related research tasks including: a modeling evaluation of the effects on energy and indoor air quality of various means of demand-controlled ventilation for controlling minimum ventilation rates in California commercial buildings; a field assessment of the performance of two commercially available technologies for measuring rates of outdoor air intake into air handlers; and sets of experiments that evaluated the performance of carbon dioxide sensors and people counters for use as part of building ventilation rate control systems. Results of this research were used to develop occupancy-specific guidelines for using carbon dioxide sensors in demand-controlled systems, measuring ventilation rates, and developing guidance on selection and use of technologies for measuring outside air intake rates.

Keywords: Commercial buildings, energy, indoor air quality, ventilation standards, demand-controlled ventilation, carbon dioxide sensor

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EXECUTIVE SUMMARY

Introduction

Energy efficiency is a critical element of California's energy policies to reduce emissions of greenhouse gases that cause climate change and improve the energy performance of the state's economy. California's Title 24 building efficiency standards have saved customers billions of dollars over the last four decades and contributed to state per capita electricity consumption remaining relatively flat since the mid-1970s. The standards ensure that builders use the most energy-efficient technologies and construction practices.

Minimum building ventilation rates are one of the requirements in the Title 24 standards. Proper building ventilation is essential for the comfort, health, and productivity of the millions of people who spend much of their time in office or school buildings. Ventilation systems help protect indoor air quality by bringing in outside air to dilute the build-up of carbon dioxide and other indoor air pollutants generated by building occupants and in some cases by the buildings themselves (for example, carpets and other furnishings). However, facility managers must monitor and control building ventilation rates to bring in enough outside air to maintain safe levels of carbon dioxide and indoor pollutants, but not so much that the building's heating, ventilation, and air conditioning system will have to work harder, resulting in wasted energy and higher energy costs. Research has shown that ventilation rates in commercial buildings can affect occupant health, performance, and energy consumption, but these rates are often poorly controlled. Better measurement and control systems could increase building energy efficiency, reduce energy waste and costs, lessen adverse health effects, and increase productivity.

Project Purpose

The main purpose of this project was to identify strategies to provide better control of outside air ventilation rates in existing and new commercial buildings in California and enable buildings to meet the minimum ventilation rate requirements of California's Title 24 building efficiency standards. With better control systems for ventilation rates, buildings can avoid over-ventilation that can waste energy and increase energy costs, as well as under-ventilation that can increase adverse health effects and decrease school and work performance. This project is particularly relevant to natural gas efficiency: minimum ventilation rates affect heating that is usually supplied using natural gas more than cooling, which is usually supplied by electricity.

Project Approach and Results

This project included five studies.

Energy and Indoor Air Quality Advantages of Control of Ventilation Rates

Demand-controlled ventilation strategies adjust outside ventilation air based on the number of occupants and the ventilation demands those occupants create. Controlling minimum ventilation rates using these strategies can save energy while maintaining acceptable indoor air quality. This study analyzed the energy and indoor air quality advantages of controlling minimum ventilation rates based on occupant count, carbon dioxide concentration, and the predicted indoor concentrations of a continuously emitted indoor pollutant.

The analysis showed that using these strategies in densely occupied buildings reduced the predicted energy used for heating, ventilation, and air conditioning on average by about 10 percent statewide compared to reference buildings. Savings varied substantially by climate zone and building type but very little by the strategy used. For small, medium, and large offices, the model showed greater energy savings compared to reference buildings whose ventilation rates exceed the Title 24 minimum ventilation rates.

The analysis of using demand-controlled ventilation systems in schools showed that the predicted energy use from heating, ventilation, and air conditioning was very similar to the energy used in reference school buildings that do not meet the minimum ventilation rates specified in Title 24 standards for schools. This suggests an opportunity to improve indoor air quality in schools using demand-controlled ventilation without using considerably more energy compared to current practice.

The demand-controlled ventilation strategies assessed in this project provide the most significant ventilation benefits for high occupancy spaces because the baseline constant ventilation strategy often over-ventilate these spaces. In areas and seasons with cooler temperatures, demand-controlled ventilation systems have a larger effect on indoor air quality and energy use. This is because the economizer is used less often in these areas. An economizer allows the cooling unit to use outside air for cooling when the temperature is cooler than the recirculated air. When they are not used often, demand-controlled ventilation system will results in larger energy savings.

Evaluation of Commercially Available Technologies for Measuring Outside Air Intake Flow Rates

To meet the Title 24 ventilation requirement, accurate measurement of flow of outside air is necessary. This study evaluated the accuracy of two commercially available outside air flow measurement technologies: the Ruskin Electronic Air Measuring Station and the Ebtron Gold probe system. The researchers evaluated the accuracy of the two technologies by comparing their reported air-flow rates to those of highly accurate air flow meters.

Measurement accuracy of the two systems was within the 3 percent to 5 percent range at higher air velocities (3 meters per second). However, measurement errors increased at the lower air velocities that occur when measuring heating, ventilation, and air conditioning systems that have economizers. For the Ebtron Gold probe system, errors increased to 50 percent or more at the lowest air speed (0.3 meters per second). The Ruskin Electronic Air Measuring Station demonstrated an error of 25 percent at 0.5 meters per second when tested with a horizontal-blade louver and an over-prediction of 30 percent to 40 percent when tested with a vertical-blade louver.

The evaluation suggests that the design of the upstream louver or air intake hood strongly affects the accuracy of outside air measurement technologies, so technology manufacturers need to provide information on measurement accuracies that is specific to the louver or air intake hood used. Results also indicate that the two technologies tested in this study will often have high measurement errors when used to measure minimum ventilation rates in systems with economizers.

Long-Term Assessment of Carbon Dioxide Sensors Marketed for Use in Demand-controlled Ventilation Systems

Carbon dioxide sensors are a common method for measuring building occupancy and are an essential component of demand-controlled ventilation strategies. The higher the level of carbon dioxide, the more people are in the space relative to the ventilation rate.

This study evaluated the accuracy of seven carbon dioxide sensors for two years in three spaces—general office space, conference room, and classroom—by comparing the concentrations of carbon dioxide measured using the sensors with the concentrations measured using a high-accuracy reference instrument. The evaluation looked at seven sensor models, including sensors from five manufacturers (AirTest, BAPI, Gas Sensing Solutions, Telaire, and Vaisala) and five different types of sensors (single-beam single-wavelength, single-beam dual-wavelength, with and without auto-calibration algorithm, and different infrared sources including a light bulb, a MEMS emitter, and a light-emitting diode). The team installed 21 sensors, three of each of the 7 models, in each of the three study spaces and recorded data at one-minute intervals. Accuracy of the reference instrument was checked using a multi-point calibration about once a month throughout the two-year study.

The resulting data showed differences in accuracy by manufacturer and by type of sensor. Four of the seven sensors—AirTest TR9294, BAPI Stat 4, Telaire T8100, and Vaisala GMW86—had an absolute value error less than 75 parts per million more than 95 percent of the time in the general office space. For reference, the accuracy range specified by the California Title 24 building efficiency standards for carbon dioxide sensors is ±75 parts per million. The "dual channel" models by BAPI (Stat 4 24/7) and Telaire (T8200) agreed with reference instrument less often in the general office space, with absolute value error greater than 75 parts per million about 20 percent of the time. The COZIR (Gas Sensing Solutions) model did not agree well with the reference carbon dioxide instrument, with absolute value error greater than 75 parts per million more than half of the time in all three study spaces.

The accuracy of the carbon dioxide sensors also varied somewhat among the three study spaces. Some carbon dioxide sensors performed similarly in all three spaces; others varied among the space types, with the lowest errors tending to occur in the general office space where carbon dioxide concentrations varied the most gradually during the day with daily peak carbon dioxide concentrations typically between 600 and 700 parts per million. Some carbon dioxide sensors (Telaire T8100 and T8200, Vaisala GMW86) had higher errors in the classroom, which had higher average carbon dioxide concentrations. Other sensors (BAPI Stat 4 and Stat 4 24/7) had higher errors in the conference room, which had generally low carbon dioxide concentrations but also periods of rapidly increasing, and sometimes high, carbon dioxide concentrations.

This study also found lower absolute values of error among the selected sensors compared to a prior study done by Fisk, Faulkner et al. (2009). The prior study found the averages of absolute values of error were 118 parts per million (16 percent) and 138 parts per million (14 percent) at concentrations of 760 parts per million and 1010 parts per million, respectively. In the study conducted for this project, the average of mean absolute values of error of the seven carbon dioxide sensors was 7 percent and differed by manufacturer and sensor type.

During the two-year evaluation, the study data indicate systematic changes in errors over time in a small number of sensors and only in some study spaces. The results suggest that periodic replacement of carbon dioxide sensors used for demand-controlled ventilation alone is not enough to guarantee accuracy. Carbon dioxide sensors should also be checked shortly after installation to ensure they are functioning properly.

Accuracy of People Counters for Use in Controlling Building Ventilation

Along with carbon dioxide sensors, other people-counting technologies can measure building occupancy for demand-controlled ventilation systems. This study evaluated infrared camera and infrared beam technologies in two test locations: a building with double doors opening to the exterior, and a conference room with a single-wide interior door. Infrared cameras can provide reliable occupant counts in spaces with exterior double doors, while the infrared beam sensor is only suitable for spaces with single-wide doors like a conference room. Both sensors are trying to provide an accurate count of people inside the building, therefore, provide proper amount of ventilation. The study showed that use of the infrared beam technology would result in ±10 percent of the required ventilation in a conference room, if counting were the only cause of error. Use of the infrared camera counter would result in ±20 percent of the required ventilation rate in a building with a double-door entrance.

For both test locations, the predicted average carbon dioxide concentrations in the space deviated by roughly ±25 parts per million from the concentrations expected with perfectly accurate people counting. On average, using these infrared people counters to control ventilation rates would result in indoor carbon dioxide concentrations within the ±75 parts per million accuracy range specified in the California Title 24 building standards for carbon dioxide sensors. However, when used at the more-challenging exterior door location, an error of ±20 percent of the required ventilation rate may not be acceptable to meet the energy saving goals of demand-controlled ventilation. Further consideration of the costs and long-term performance of people counters is needed for this technology to be recommended for use with demand-controlled ventilation.

Method for Measuring Building Ventilation Rate Based on Measured Carbon Dioxide and Occupant Counts

This study applied a model to estimate ventilation rates using carbon dioxide concentrations and people counts measured in two office spaces for two weeks each. The researchers determined the accuracy of the estimated rates using this transient method by comparing them with a reference ventilation rate measured using tracer gas decays (by introducing a specific type of gas into the flow and using the known decay behavior of such gas to determine the ventilation rate). In addition, the researchers computed ventilation rates using a steady state (time independent) method, using measurements of peak carbon dioxide and peak occupancy to calculate ventilation rates.

Using the transient model, ventilation rates agreed with the reference value on average. However, substantial day-to-day variability in the estimated ventilation rates suggests that multiday carbon dioxide and occupancy data are needed to accurately estimate the ventilation rate if this method is used.

In the office setting, ventilation rates calculated using the steady-state assumption and actual occupancy also agreed with the reference value on average. However, other types of building spaces (for example, classrooms) may have more variable occupancy patterns where the steady-state method may not apply.

The research team found site-specific challenges to using an infrared camera to determine people counts. Counting errors were more influential in small spaces with low occupant counts, when the data are used to calculate ventilation rates. Site-specific guidelines are needed to help users of people counting technologies to ensure that the system is giving accurate data, if the data is used to measure and/or control ventilation rates.

Knowledge Transfer

Findings from this project were presented to the Technical Advisory Committee (TAC), which is composed of members from industry and the research community with technical expertise in the area of building ventilation. TAC members from NORESCO, Taylor Engineering, and Trane provided industrial perspectives ranging from energy service provider to equipment manufacturer. The findings were also shared with American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standing Standard Project Committee 62.1 and the Energy Commission building efficiency program staff to get insights on building ventilation standards consideration.

The ASHRAE 62.1 Committee is responsible for setting standards for ventilation for acceptable indoor air quality, and the Energy Commission's building efficiency program sets the ventilation standards through the Title 24 building code. Their involvement enabled knowledge from this project to inform future standard updates regarding mechanical ventilation. Industries can use this project's evaluation of technologies for measuring and controlling minimum ventilation rates to inform the design of new technologies or the improvement of existing products. TAC members used this project's results to identify the need for future research to improve people counting technology.

Recommendations on various aspects of measurement and control of ventilation rates were made available on the project website (http://ventcon.lbl.gov) that included: an introduction to demand controlled ventilation strategies and energy savings for California; a discussion of required accuracy for CO2 sensor selection, calibration, and placement; and a review of technologies for measuring outdoor air. Important findings from this project were incorporated in the recommendation sections of the website.

Project Benefits

This project has provided new data that will help building and heating, ventilation, and air conditioning designers decide whether and how to employ demand-controlled ventilation or outside air measurement technologies in California's commercial buildings. Adoption of demand-controlled ventilation will reduce ventilation energy consumption and provide adequate outdoor air to buildings, thus improving indoor air quality. In addition, the data from this project can inform future specifications of California's Title 24 standard pertaining to demand-controlled ventilation and requirements for outside air measurement technologies.

Conclusions and Recommendations

This project has demonstrated that demand-controlled ventilation systems can save substantial energy in offices with high occupant density, and improve indoor air quality in schools with minimal changes in energy use. The project has shown how the energy impacts of demand-controlled ventilation vary with building type and location within California. The evaluation of two outside air measurement technologies systems indicates a need for outside air measurement technology calibrations that vary with installation conditions. For outside air measurement technologies to accurately measure minimum ventilation rates, their accuracy in measuring low air velocities must improve. The project's evaluation of carbon dioxide sensors has indicated some improvements in measurement accuracy relative to prior data. There is still a need to check the accuracy of carbon dioxide sensors immediately after they are installed, even if they were newly purchased and factory calibrated. The project has shown that the two people-counting technologies evaluated are, in general, sufficiently accurate for demand-controlled ventilation applications, although accuracy over time still needs to be assessed. Finally, the project data indicate high measurement imprecision, but reasonable long-term average estimates of ventilation rates, using transient people count and carbon dioxide data collected from two office spaces. This project tested the use of people counting technologies in different settings and found site-specific challenges, such as occupant behaviors, spatial dimensions, and environmental factors at the installed site that affected the counting accuracy of the technology. There is a need for guidelines to help users of people-counting technologies to obtain sufficiently accurate data for measurement and control of ventilation rates.

CHAPTER 1: Background

Outdoor air ventilation must be provided in buildings to control indoor concentrations of indoor-generated air contaminants that may adversely affect indoor air quality. Ventilation rates (VRs) in commercial buildings affect health, productivity, energy consumption, and energy costs. A variety of studies have shown that lower VRs are associated with increased sick building syndrome symptoms and dissatisfaction with indoor air quality (IAQ) in offices. Sick building syndrome is a condition affecting office workers, typically marked by headaches and respiratory problems, attributed to unhealthy or stressful factors in the working environment such as poor ventilation. Lower VRs are also associated with decreases in work and school performance. Controlled experimental studies show that higher concentrations of carbon dioxide (CO_2) and lower rates of ventilation reduce the decision-making performance of building occupants. Three classroom studies, one daycare study, and one office study have documented higher absence rates when there is inadequate ventilation. However, modeling studies indicate only small increases in the risk of chronic health effects such as cancer with inadequate ventilation.

Modeling studies by the Lawrence Berkeley National Laboratory (LBNL), the National Renewable Energy Laboratory, and the United States Environmental Protection Agency (USEPA) indicate that VRs extensively affect the energy consumption of heating, ventilation, and air conditioning (HVAC) systems. Data also indicate that VRs are often poorly controlled, usually exceeding California's Title 24 building energy efficiency requirements in offices and retail buildings, but often far less than Title 24 requirements in schools. In essence, this means that office and retail buildings are often over-ventilated, resulting in wasted energy as the outside air is heated and cooled, while schools can be under-ventilated and not meet the legal standard.

At present, many commercial building HVAC systems do not include technologies to measure minimum ventilation rates (MVRs) in real time, which increases the risk of under- and over-ventilation. Practical and reasonably accurate measurement systems for MVRs can help building managers to achieve better control of MVRs and improve the performance of their buildings.

Project Overview

LBNL's project included several experimental tasks to evaluate different technologies that can improve real-time measurement and control of VRs. The work included:

- Follow up on prior evaluations of commercially available technologies for real-time measurement of flow rates of outdoor air (OA) into air handlers, called outdoor airflow measurement technologies (OAMTs).

- Evaluation of the accuracy over time of in-use current-generation CO_2 sensors marketed for demand-controlled ventilation or DCV, which involves automatically adjusting building ventilation based on how many occupants are in a building and their ventilation needs.
- Evaluation of the accuracy and practicality of counting building occupants using new technologies, building on a limited prior evaluation of occupant counting systems.
- Evaluation of the accuracy of determining VRs using calculations based on CO_2 measurements and occupancy counts.

In addition, the project modeled the energy, peak electricity demand, and IAQ advantages of DCV with control of MVRs based on: (1) use of a CO_2 sensor to keep indoor CO_2 concentrations below a certain threshold; (2) occupant count; (3) a mass balance calculation to limit the indoor concentration of a generic contaminant emitted indoors continuously; and (4) limiting the indoor concentrations of both the generic contaminant and CO_2. Items (3) and (4) should capture energy savings by enabling temporary reduction of MVRs after periods of very high VRs from activating an economizer (which allows a unit to use outside air for cooling when the temperature is cooler than the recirculated air), while still maintaining low indoor pollutant concentrations. The project also evaluated the effects of CO_2 measurement error on energy consumption and IAQ in buildings with VRs controlled by CO_2 concentrations.

This project developed new data that will help building and HVAC designers and building operators decide whether and how to employ DCV or OAMTs in California's commercial buildings. The project also produced data that can be used in future updates to the Title 24 standards pertaining to DCV and requirements for OAMTs. The information gained in this research will also aid manufacturers in product evaluation and product improvement.

This project benefits Californians by enabling better measurement and control of VRs in their buildings. With better control systems for VRs, excessive VRs that waste energy and increase energy costs can more often be avoided. Insufficient ventilation that increases adverse health effects and decreases school and work performance can also be avoided. The project is particularly relevant to natural gas, because MVRs affect heating energy use, usually supplied by natural gas equipment, more than cooling energy that is usually supplied by electricity.

Effect of Ventilation on Indoor Air Quality and Energy Use

This research is needed for two reasons. First, VRs in commercial buildings affect health, work and school performance, and energy consumption. Second, VRs are often poorly controlled. Previous studies document that lower VRs are associated with increased sick building syndrome (SBS) symptoms and decreased satisfaction with IAQ in office workers (Seppanen, Fisk et al. 1999, Fisk, Mirer et al. 2009, Sundell, Levin et al. 2011). Lower VRs are also associated with decreases in work and school-work performance (Seppanen, Fisk et al. 2006, Wargocki and Wyon 2007, Haverinen-Shaughnessy, Moschandreas et al. 2011). In tightly controlled experimental studies, decision making performance was reduced with higher CO_2 concentrations (Satish, Mendell et al. 2012) and with lower VRs per person and per unit floor area (Maddalena, Mendell et al. 2013). Three classroom studies, one daycare study, and one office study have documented increased absence rates with less ventilation (Milton, Glencross et al. 2000, Shendell, Prill et al. 2004, Mendell, Eliseeva et al. 2013, Gaihre, Semple et al. 2014, Kolarik, Andersen et al. 2016). Modeling studies indicates only small increases in risks of chronic health effects, such as cancer, with less ventilation (Chan, Parthasarathy et al. 2016).

Existing data also indicate that VRs are currently often poorly controlled, usually over-ventilate in offices and retail buildings compares to Title 24 requirement (Persily and Gorfain 2008, Bennett, Fisk et al. 2012, Siegel, Srebric et al. 2012, Chan, Sidheswaran et al. 2013), but often under ventilate in schools (California Air Resources Board 2004, Mendell, Eliseeva et al. 2013, Fisk 2017). In general, commercial building energy use, particularly use of gas for heating, is greatly increased with higher MVRs, but in some cases higher VRs in buildings without economizer controls can save energy (EPA 2000b, Benne, Griffith et al. 2009, Dutton, Brunswick et al. 2014) because the higher ventilation airflows reduce electricity use for cooling. Peak electricity demands are also affected by MVRs. Consequently, there is a critical need for research on the benefits of, and technologies for, controlling VRs in California’s commercial buildings, including classrooms. This project addresses these critical needs.

State of Current Technologies

Many commercial buildings have economizer controls that increase VRs above the MVR to save cooling energy when weather is mild. In these buildings, the measurement and control of MVRs that occur when economizers are not activated, and which are prescribed in standards, is most critical. At present, many commercial building HVAC systems contain no technologies for real-time measurement of MVRs.

One approach to measure MVRs is to add technologies for real-time measurement of the rates of OA flow into air handlers, with several technologies being marketed today. While the mechanical ventilation provided by air handlers is the key focus of HVAC designers, considerable additional ventilation may occur via air infiltration through the building envelope. Measurements of OA intake rates are challenging because of the low air speeds in OA intake sections of air handlers when MVRs are provided and because of the complex airflow patterns in many OA intakes passages (Fisk, Faulkner et al. 2005b, Han, Sullivan et al. 2010). The project team previously evaluated several of these technologies and none provided a consistently satisfactory measurement at minimum OA conditions in HVAC systems with economizers, which are very common in

California (Fisk, Faulkner et al. 2005a, Fisk, Faulkner et al. 2005b, Fisk, Faulkner et al. 2005c). However, newer technologies have since been developed and some may have addressed the measurement problems noted in prior research (Fisk, Faulkner et al. 2005b, Fisk , Cohen et al. 2008).

DCV is a second approach used today for controlling MVRs. It is most often used in spaces with a high occupant density and is required by Title 24 for certain types of spaces. In the usual application of DCV, CO_2 sensors are installed indoors and control systems modulate MVRs to maintain indoor CO_2 levels below a set point. DCV, if it functions as intended, maintains a MVR per person and accounts for ventilation by infiltration, but this form of DCV does not maintain a MVR per unit floor area. (California's Title 24 specifies that buildings maintain the larger of a MVR per person and a MVR per unit floor area.)

DCV can save energy by enabling the MVR to be modulated as occupancy varies (Fisk and de Almeida 1998, Brandemuehl and Braun 1999, Emmerich and Persily 2001, Hong and Fisk 2010). LBNL's prior research found that the CO_2 sensors deployed for DCV applications in California often had large errors, making DCV unreliable (Fisk, Sullivan et al. 2010). Research by the Iowa Energy Center showed that new CO_2 sensors also often had large errors (National Buildings Controls Information Program 2009). However, sensor technologies are continuously improving. Subsequent quarterly calibration checks over a full year of 66 deployed CO_2 sensors of one brand and model provide some evidence of improvements in sensor performance (Mendell, Eliseeva et al. 2015).

Because the accuracy of CO_2 sensors used for DCV has often been poor, it is of interest to identify alternative types of sensors that may be used in DCV systems. Research by Kuutti, Blomqvist et al. (2014) and Erickson, Achleitner et al. (2013) indicates that there are energy savings from optimally controlling HVAC systems in buildings based on actual occupancy levels. Some buildings are already using occupant counting sensors for various purposes such counting customers in retail stores or visitors to museums. Occupant counting sensors are potentially more robust than the CO_2 sensors commonly used in DCV. In some situations, occupant-counting sensors may be less costly than CO_2 sensors for DCV, or may lead to more accurate control of VRs.

One potential challenge of using occupant counting for DCV is the need for more complex control algorithms to optimally meet the ventilation requirement of a space. Compared to DCV based on people counts, CO_2-based DCV has two inherent advantages. First, CO_2-based DCV responds to the indoor concentrations of CO_2, an occupant-generated bioeffluent, and thus automatically adjusts for the lags in indoor CO_2 concentrations after a change in occupancy or change in VR. Second, CO_2-based DCV also adjusts automatically for the variability in emission rates of bioeffluents with changes in occupant activity levels. DCV based on occupant counters lack these two advantages. With more complex control algorithms, occupant-counter-based DCV could incorporate suitable lags, for example a delay in the increase in VR after an increase in occupancy. Also, known activity levels could be input into control algorithms.

The two identified prior studies most closely related to the current task are Fisk and Sullivan (2009) and Kuutti, Blomqvist et al. (2014). Fisk and Sullivan (2009) evaluated two occupant counting technologies. At the time of evaluation, one of the technologies was on the market primarily for use in retail buildings, and the second was a prototype under development that appears to have not made it to market. The first technology used a low-resolution camera mounted above a doorway and algorithms to detect and count people passing in infrared (IR) each direction through the camera's view. The operating principal of the second system was not disclosed, but likely also involved an IR camera or a passive IR system. The authors evaluated counting accuracy with systems installed at a multidoor entrance to an office building, a single-door entrance to a conference room, and a single-door entrance to a laboratory. The evaluations assessed the accuracy of people counting with visual observations of people's movement and record keeping providing the reference counts. The evaluations included controlled "challenges" of the counting systems using pre-planned movements of occupants through doorways and evaluations of counting accuracy when occupants unaware of the counting system passed through the entrance doors of the building or room. Some of the controlled challenges were highly demanding and may infrequently be encountered in practice, but served to elucidate the range of applicability of the technologies. The two people counting systems were very accurate for typical non-demanding counting events, with errors typically less than 10 percent. However, counting errors were high in some challenging situations, such as multiple people passing through a door together. For at least one system, counting errors can be very high if people stand in the field of view of the sensor.

Kuutti, Blomqvist et al. (2014) evaluated eight counting technologies at the entrance to a café from a corridor in a factory building. Five of the technologies distinguished between people entering and exiting the café. Two of the technologies employed IR light beams and cameras (technologies used were from outside of the United States). Three technologies were direction insensitive and consequently will not be discussed further.

The best performing technology, a device that employed light beams, had a counting error of approximately 4.6 percent in one travel direction and 5.2 percent in the other. These two errors largely canceled out (5.2 percent minus 4.6 percent equals 0.6 percent) in calculations of the number of occupants. One of the camera-based sensors had errors of 3 percent for travel in one direction and errors of 7 percent for travel in the opposite direction. Other technologies had larger counting errors, as high as 22 percent.

Currently, VRs per person are normally estimated from peak indoor CO_2 concentrations, assuming occupancy and VR are stable for a sufficient period to reach equilibrium. These estimations can be highly uncertain, even when the CO_2 measurement is accurate, because VRs and occupancy vary over time and the assumed equilibrium conditions are not attained. Batterman (2017) applied different methods to estimate

VRs in four classrooms and found that the transient mass balance model was the most suitable given the low VRs and dynamic occupancy patterns observed in classrooms. Work in this area will also build upon past experience of the research team in estimation of VRs from CO_2 data using steady state and transient mass balance models, including, most recently, the data collected during two years from 160 classrooms (Mendell, Eliseeva et al. 2013) and during one year from 16 office spaces (Mendell, Eliseeva et al. 2015).

Practical Implications

This research is important because manufacturers of the associated technologies have no incentive to support independent performance evaluations given the risk that the research will identify problems with their technologies. Prior research has shown that manufacturers' accuracy claims for CO_2 sensors and technologies that measure OA intake rates are frequently not realized in practice. For example, many CO_2 sensor manufacturers provide accuracy specifications for their products that precisely match the accuracy requirements in Title 24, while independent studies have shown that accuracy is often much poorer. Evaluating the accuracy of technologies that measure rates of OA intake into air handlers as weather conditions and winds vary requires a special test system and LBNL believes it has the only such test system. Finally, the broad characterization of the effects of minimum VRs and associated control methods on energy use in California is primarily needed to facilitate development of standards and policy; thus, companies have little incentive to perform such research.

CHAPTER 2: Overall Methods

This chapter provides an overview of the two technical tasks listed in Chapter 1, why the project team selected the DCV strategies for modeling in EnergyPlus, and how the team selected VR measurement and control technologies or sensors for evaluation. Chapter 3 provides detailed information on the research methods and results for each of the technical tasks.

Energy and Indoor Air Quality Impacts of Control of Ventilation Rates

The team used EnergyPlus to model the energy and indoor air quality implications of four DCV strategies: (1) use of a CO_2 sensor to limit indoor CO_2 concentrations to below a threshold; (2) occupant count; (3) a mass balance calculation to limit the indoor concentration of a generic contaminant that is continuously emitting inside a building; and (4) limiting the indoor concentrations of both the generic contaminant and CO_2. Six different commercial buildings were modeled (primary and secondary schools; small, medium, and large offices; and stand-alone retail building) in each of California's 16 climate zones.

The EnergyPlus modeling method was similar to prior modeling of how different fixed MVRs in offices affect energy consumption and indoor air quality (Dutton, Brunswick et al. 2014). The project modeled two baseline or reference conditions: (1) Title 24 compliant MVRs without DCV, and (2) estimated average MVRs observed in surveyed office buildings and classrooms, also without DCV. Baseline (2) was based on empirical data indicating that MVRs in general office spaces often far exceed MVR requirements in Title 24 standards (Persily and Gorfain 2008, Bennett, Fisk et al. 2012, Mendell, Eliseeva et al. 2015). As a result, DCV could save energy by reducing over ventilation in offices. Empirical data also indicate that MVRs in classrooms often fall far short of the MVRs specified in standards for classrooms (California Air Resources Board 2004, Mendell, Eliseeva et al. 2013). DCV could reduce the widespread under-ventilation of classrooms, although potentially with an increase in energy use.

Minimum Ventilation Rate Control Strategies

California's Title 24 standards require use of DCV in spaces with a design floor area per occupant less than 3.7 square meters with several exceptions, for example classrooms and spaces with a total floor area less than 14 square meters (California Energy Commission 2013). However, DCV is sometimes used in general office spaces, retail buildings, and classrooms. DCV systems typically employ CO_2 sensors and modulate the rate of outdoor air supply to maintain the indoor air CO_2 concentration below a set point, typically 1,000 ppm (600 ppm above an assumed ambient CO_2 concentration of 400 ppm).

While nearly all of today's DCV systems employ CO_2 sensors, prior research indicates that CO_2 sensor accuracy is often poor (National Buildings Controls Information Program 2009, Fisk, Sullivan et al. 2010) making it worthwhile to consider other types of sensors and control schemes. An option is to employ devices that track the number of occupants in a building or region of a building and then to vary the MVR as the occupancy varies. If desired, the control algorithms can incorporate lags in changes in MVR that account for the lags in changes in indoor air bioeffluent concentrations after occupancy varies. ASHRAE standard 62.1 permits DCV based on devices that directly count or otherwise estimate numbers of occupants in a space. Currently, Title 24 permits CO_2-based DCV only; occupant counts cannot be used as an alternative to CO_2.

For buildings with HVAC systems with economizers, there is another MVR control option with the potential to save energy that requires no indoor air quality sensors or people counters. As mentioned above, when economizers are activated, VRs are typically several times the MVR. The high VRs reduce indoor air concentrations of indoor-generated air pollutants to far below the concentrations that occur with continuous ventilation at the MVR. Thus, after an extended period of economizer activation, MVRs could be reduced for a considerable time while indoor air pollutant concentrations rise toward the concentrations that occur at steady state when providing the specified MVR. This would save energy during the period of reduced MVR, while maintaining indoor air concentrations of air pollutants below the levels associated with the MVR prescriptions of standards. The period after economizer activation has ceased during which the MVR can be reduced was determined via a mass balance model of the indoor concentration of a hypothetical indoor-generated air pollutant that is emitted at a constant rate regardless of occupancy, for example, emissions of pollutants from building materials and furnishings. An additional control strategy is modeled by combining this strategy with CO_2-based DCV.

Effects of Carbon Dioxide Sensor Accuracy

Currently, Title 24 standard requires that the measurement errors in CO_2 sensors used for DCV be certified be no greater than 75 parts per million (ppm) for five years after sensor installation. The team performed a sensitivity analysis to examine the significance of the accuracy of CO_2 sensors. Two additional scenarios were tested that repeated the CO_2 set points of 900 ppm and 1,100 ppm in addition to the reference 1,000 ppm. These scenarios were used to estimate the statewide effect of an offset in the CO_2 sensor accuracy.

Technologies for Measurement and Control of Ventilation Rates

The team consulted with Technical Advisory Committee (TAC) members, including representatives of a leading HVAC design and control firm and a leading HVAC manufacturer, on the following technologies for evaluation. All selections were also approved by the Energy Commission's contract manager.

- Outdoor airflow measurement technologies (OAMTs).
- CO_2 sensors marketed for DCV.
- People counters.

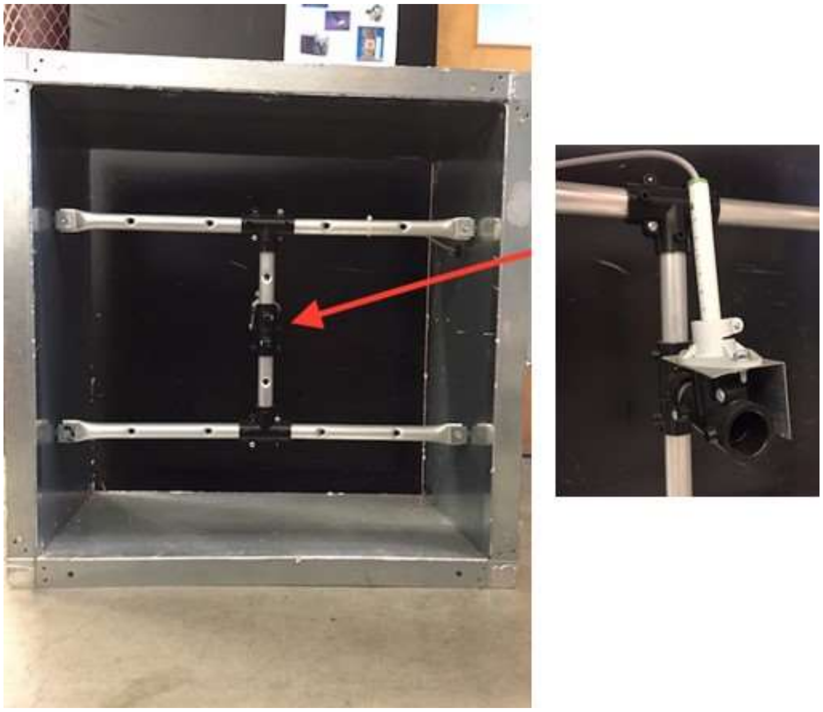
Outdoor Airflow Measurement Technologies

The accuracy of four commercially available OAMTs had been previously evaluated (Fisk, Faulkner et al. 2005a, Fisk, Faulkner et al. 2005b, Fisk, Faulkner et al. 2005c). Also, prototypes of modified existing OAMTs and entirely new OAMTs had been evaluated (Fisk, Chan et al. 2015). The prior evaluations of commercially available technologies documented large measurement errors under some operating conditions. The errors were due, in part, to low air speeds when minimum outdoor air is supplied. Tests of prototypes showed how to overcome these challenges by including components that condition the airflow upstream of velocity sensors and use of sensors that can accurately measure the air speeds encountered.

Based on these prior experiences, the team selected two commercially available OAMTs in consultation with the TAC. Members of the TAC with related expertise indicated a clear preference for evaluating OAMTs marketed by Ruskin and Ebtron (for Ebtron, the Ebtron Gold probes were a priority) because they were the most widely used. The TAC also recommended not including airflow straighteners because they are rarely used in practice.

The Ruskin EAMS (Electronic Air Measuring Station, Figure 1) directs air from the multiple ports of a manifold through a single-point electronic airflow sensor.

Figure 1: Ruskin Electronic Air Measuring Station



Ruskin EAMS has a digital controller (not shown) that was installed to the side of the unit following manufacturer's Installation and Maintenance Manual.

Source: Lawrence Berkeley National Laboratory

The system is advertised for a velocity of 0.51 meters per second ($m\ s^{-1}$) to 10.1 $m\ s^{-1}$ (100 to 2,000 feet per minute [fpm]). The manufacturer's Installation and Maintenance Manual[1] states that EAMS measures "the minimum ventilation airflow to within ± 3 percent accuracy." The EAMS was evaluated when installed as specified by the manufacturer: downstream of the Ruskin EME3635 vertical blade louver in one series of tests, and downstream of the Ruskin 375DX horizontal blade louver in another series of tests.

The Ebtron Gold probes have multiple thermal dispersion air velocity sensors spaced along a tubular probe. The measurement system uses one or more probes together with electronics that power the probes and output a signal proportional to the average air speed. Two probes were used in the testing (Figure 2). The manufacturer indicates[2] that the Ebtron Gold system is usable for air velocities of 0 $m\ s^{-1}$ to 25.4 $m\ s^{-1}$ (0 to 5,000 fpm), and that probes should be installed at least 30.5 centimeters (cm) (12 inches) downstream of a louver, and 15.2 cm (6 inches) downstream of the outlet plane

1 Ruskin Electronic Measuring Station (http://www.ruskin.com/file/doc/2871).

2 Ebtron Gold System (https://ebtron.com/wp-content/uploads/documents/IG_P_INS.pdf, https://ebtron.com/wp-content/uploads/documents/IG_GTC116.pdf).

of an air intake hood. Probes should also be installed at least 15.2 cm (6 inches) upstream of the upstream edge of OA damper blades when the damper is open. The manufacturer's specified accuracy for non-ducted OA intakes is better than or equal to ± 5 percent of the reading.

Figure 2: Ebtron Gold Probe System

Ebtron Gold probe system (24"x24" Model GTC-116-P+ AFMS) used in the testing.

Source: Lawrence Berkeley National Laboratory

Evaluations of accuracy of the Ebtron Gold system were performed with two air intake hoods of typical design. Previous research evaluated the use of the Ebtron velocity probes installed downstream of various types of louvers, with and without airflow straighteners (Fisk , Cohen et al. 2008). The prior study found that measurement accuracy was sometimes poor, primarily because the upstream louvers cause the velocity profile in the plane of the probes to be highly non-uniform. The air velocity profile downstream of an air intake hood may be more uniform than the velocity profile downstream of a louver. Consequently the Ebtron Gold system was anticipated to provide a consistently more accurate measurement of airflow when the probes are installed downstream of an air intake hood, relative to downstream of a louver.

Each OAMT was installed in a unique test system located on the roof of a building at Lawrence Berkeley National Laboratory (LBNL). A roof top location was desirable because wind speed and direction can affect the accuracy of an OAMT. The airflow rates indicated by the OAMTs were compared to airflow rates determined using downstream highly accurate nozzle flow meters.

Carbon Dioxide Sensors Marketed for Demand-controlled Ventilation

In a prior evaluation of the accuracy of 208 deployed CO_2 sensors, measurement accuracy was often insufficient for well-functioning DCV systems (Fisk, Sullivan et al. 2010). The average absolute value error was 154 ppm with a standard deviation of 263 ppm. Thirty six percent of sensors had an error greater than 100 ppm. A laboratory-based study of the initial accuracy of 15 models of new sensors also noted large errors greater than 75 ppm, and errors greater than 200 ppm were not unusual (National Buildings Controls Information Program, 2009). The accuracy of currently marketed CO_2 sensors has likely changed since publication of the above studies, as manufacturers of CO_2 sensors for DCV frequently upgrade their products, in part to improve accuracy.

Seven CO_2 sensors (Figure 3) were selected for accuracy evaluation over two years in three spaces with different CO_2 concentration-time profiles: general office space, conference room, and classroom. The selected sensors span a range of designs from sensor manufacturers with a large market share. All are non-dispersive infrared (IR) sensors that determine the CO_2 concentration based on the amount of adsorption of an IR light beam. Each sensor contains a cell with a source of IR light and an IR detector that measures the amount of incident IR light. All selected sensors are designed to measure in the 0–2000 ppm concentration range, and rely on diffusion through a membrane to maintain the same concentration of CO_2 inside the cell as in the surrounding environment.

Three of the sensors tested (BAPI Stat 4, Telaire 8100, AirTest TR9492) employ a single wavelength of IR light and an automated background calibration. To help maintain sensor accuracy, these devices keep track of the smallest amount of IR light adsorption over a period of days to weeks and automatically adjust the sensor’s calibration, under the assumption that the lowest encountered CO_2 concentration is approximately 400 ppm. Three of the sensors (BAPI Stat 4 24/7, Telaire 8200, Vaisala GMW86) instead use a second wavelength of IR light, not adsorbed by CO_2, to automatically correct the sensor’s calibration.

Aside from these six sensors that employ a heated element at the IR source, LBNL also tested the COZIR sensor that uses a light emitting diode (LED) as the IR source. The LED source consumes less energy than the other IR sources, making it possible to power the COZIR for up to 3 years with 2AA batteries for wireless application. For this evaluation test, COZIR was powered continuously the same as the other sensors.

Figure 3: Selected Carbon Dioxide Sensors for Accuracy Evaluation Study

Source: Lawrence Berkeley National Laboratory

People Counters

Research by Kuutti, Blomqvist et al. (2014) and Erickson, Achleitner et al. (2013) indicates that there are energy savings from optimally controlling HVAC systems in buildings based on actual occupancy levels. Many different occupant counting methods have been conceived and discussed in literature. The recent review by Labeodan, Zeiler et al. (2015) summarizes common systems used in buildings for occupancy detection and counting. For this research, two directional occupant counting technologies that are used commercially were selected for evaluation: IR camera and IR beam counter. Past work by Fisk and Sullivan (2009) and Kuutti, Blomqvist et al. (2014) tested prior models of IR camera and IR beam counter, and found counting error in 5 percent to 10 percent range in some settings.

Infrared camera systems record and analyze the IR images from people as they pass through a spatial zone. Some of these systems are capable of detecting and counting people in an open space, aside from counting people flow through a doorway. With suitable software, IR camera systems mounted on ceilings can count people and determine their direction of movement even when multiple individuals pass through the zone simultaneously. The Irisys Gazelle IR camera (InfraRed Integrated Systems Ltd., United Kingdom, Figure 4) was supplied with a data processing software that reports the number of people entering and exiting the area being monitored. It can potentially count multiple people entering and exiting a doorway at the same time. This IR camera is suitable for ceiling heights typical in office buildings (2.4 to 4.3 meters, or 8 to 14 feet). Multiple cameras can be set up to communicate with one another for wide or multiple doorways. The retail cost of this device is $1,400 (+$500 for data processing software).

Figure 4: Infrared Camera Tested for People Counting

Irisys Gazelle IR camera.

Source: Lawrence Berkeley National Laboratory

IR beam systems employ multiple light beams and detectors that can sense the interruption of the beams as a person moves across it. Some systems employ IR sources and detectors at the opposite sides of a doorway. The OmniCounter (Walker Wireless, Pittsburgh, Pennsylvania) is a dual IR beam counter (Figure 5) that can detect the directional movement of people entering and exiting a doorway. The IR sensor range is 3.7 meters (12 feet). It also has a high-power option that has a range up to 6.1 meters (20 feet). The counter is battery powered. In this study, the counter was mounted horizontally in reference to the floor to give directional counts of people entering and exiting a doorway. The IR beam counter sends people counts wirelessly to a remote data receiver, which has a range of 110 feet. The retail cost of the OmniCounter is $450 (+$700 for remote data receiver). IR beam systems tend to be lower cost than camera based systems and do not have privacy concerns. However, IR beam systems have troubles distinguishing between a single person and multiple persons. If the visible camera option in an IR camera is disabled, there are also no privacy concerns because identities of individuals cannot be determined from the IR images.

The counting accuracies of the two people counting technologies, IR camera and IR beam counter, were evaluated at two test locations, a conference room and a building entrance, by comparing with observed actual counts. Scripted tests were performed to mimic challenging conditions that may make accurate people counting difficult. The test approach was similar to prior work by Fisk and Sullivan (2009).

Figure 5: Infrared Beam Counter Testing for People Counting

OmniCounter dual IR beam counter.

Source: Lawrence Berkeley National Laboratory

Methods to Determine Ventilation Rates from Carbon Dioxide and Occupancy Counts

If actual occupancy versus time is known, and a transient mass balance model is employed, it should be possible to determine VRs much more accurately than the steady-state method. The steady-state method assumes that the CO_2 generation rate is constant long enough for indoor CO_2 to reach an equilibrium concentration. This condition, however, is often not met because of variable occupancy. An advantage of using the transient approach is that it determines the total VR, unlike systems that measure rates of OA flow into HVAC systems (such as the OAMTs) which miss the ventilation that occurs by air infiltration. Also, the transient approach may be a low cost option for measurement of VRs, particularly where occupancy is already well known, such as in a call center.

CO_2 concentrations and people counts were measured in two office spaces for approximately two weeks at each location. Accuracy of people counts was characterized by comparing with manual observations. Ventilation rates determined using a transient mass balance model were compared with the reference VR, calculated using the tracer gas decay method as the true VR. The transient mass balance model and steady-state method used in this analysis are summarized in a recent review by Batterman (2017).

CHAPTER 3: Project Results

This chapter discusses the objectives, methods, and results for five studies conducted in this project:

- Energy and indoor air quality advantages of control of MVR.
- Evaluation of commercially available technologies for measuring outside air intake flow rates.
- Long-term assessment of CO2 sensors marketed for use in DCV.
- Accuracy of people counters for use in controlling building ventilation.
- Method for measuring building VR based on measured CO2 and occupant counts.

Energy and Indoor Air Quality Advantages of Control of Minimum Ventilation Rate

Objectives

To save energy, DCV is used in some buildings or spaces within a building to modulate the rate of outdoor air supply. DCV systems typically employ CO_2 sensors to maintain the indoor air CO_2 concentration below a set point, commonly set at 1,000 parts per million (ppm). This research task modeled the effects of controlling the MVRs on energy use and indoor air quality using different control strategies. The study also assessed the potential impact of error in the CO_2 sensors.

Methods

The team used the EnergyPlus building energy simulation tool to estimate the effect on energy use and IAQ of four DCV strategies in six different commercial buildings: a standalone retail building, a primary and secondary school, and small, medium, and large offices. Buildings were modeled in each of the 16 California climate zones. Comparisons were made of the heating, ventilating, and air conditioning (HVAC) energy use and indoor air concentrations of a generic indoor-generated contaminant. In addition, two baseline cases without DCV were modeled, one with Title 24 compliant MVRs and one with average actual MVRs observed in recently surveyed commercial buildings.

The four DCV strategies (discussed in more detail below) varied the MVRs based on:

1. DCV-CO_2: use of a CO_2 sensor to limit indoor CO_2 concentrations to below a threshold.
2. DCV-OCCUP: occupant count.

3. DCV-CONT: a mass balance calculation to limit the indoor concentration of a generic contaminant emitted indoors continuously.
4. DCV-CONT-CO_2: limiting the indoor concentrations of both the generic contaminant and CO_2.

In addition, the team analyzed the significance of the accuracy of CO_2 sensors. Two additional scenarios were tested that repeated the DCV-CO_2 scenario using set points of 900 ppm and 1,100 ppm in addition to the reference 1,000 ppm. These scenarios were used to estimate the statewide impact of an offset in the CO_2 sensor accuracy. Currently, the Title 24 standard requires that CO_2 sensors used for DCV be certified as no greater than 75 ppm for a period of five years after sensor installation.

Building Models

Six buildings were modeled. The modeled buildings were small, medium, and large offices, primary and secondary schools, and a standalone retail building. All buildings modeled have an economizer.

The reference small office is an approximate 400 square meter (m^2), single-zone building with an aspect ratio[3] of 2.5 and an HVAC system consisting of a packaged unit with a DX cooling coil and a heating coil (gas), economizer, and variable speed fan. The reference medium and large offices are based on United States Department of Energy reference building models (Griffith, Long et al. 2008) but have been modified to ensure that the envelope specifications comply with California's Title 24 code (2013) in each of the 16 California climate zones.

The medium office is a three-story, 5,000 m^2 building with three multiple-zone, variable air volume, packaged HVAC units. This system has three gas boilers to provide heat but also includes electric reheat coils.[4] The large office is a 12-story, 43,000 m^2 building with five thermal zones in each story. The HVAC system for the large office has two water-cooled chillers and a variable air volume HVAC system.

The primary school is a 7,000 m^2 building conditioned using multiple variable air volume and constant air volume systems for the classrooms and office space, and using a packaged single zone air conditioner (PSZ-AC) in the gymnasium, kitchen and café. The variable air volume and constant air volume systems have economizers but the PSZ-AC systems, which are very small, do not have economizers. The secondary school is a larger 20,000-m^2 building but the installed systems types mirror those in the smaller primary school.

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3 Aspect ratio is the ratio of the length to the width of the space.

4 California's Title 24 Standards prohibit reheating in many cases, but there are some exceptions. It is a limitation of this study that EnergyPlus modeling results were not verify to check if reheating is permit per Title 24 Standards.

The standalone retail store is 2,000 m^2 and has multiple PSZ-AC units, with the larger system used to condition the main retail area having an economizer.

Demand-controlled Ventilation Control Strategies

The control for the DCV strategies was implemented using a few key EnergyPlus objects:

- *Controller: OutdoorAir* object specified the economizer operation and the absolute MVR (regardless of all other control considerations) for each HVAC system.
- *Controller: MechanicalVentilation* objects defined the main control strategy.
- *DesignSpecification:OutdoorAir* objects specified the MVR calculation method.

The outdoor air *Availability Manager* object was also aligned with the occupancy schedule to ensure occupants have air when they need it. The economizer *Maximum Limit Dry-Bulb Temperature* set point[5] was 24^{O}C, above which the economizer was deactivated, and the MVR was maintained. As per California Title 24, a morning purge at a VR of three air changes per hour for one hour was performed prior to occupants entering the buildings, in all model scenarios.

Baseline MVRs were specified using the higher of a floor area-based rate specified in Title 24 2013 and an occupancy-based rate based on assumed occupant densities. The peak occupancies for the reference baseline (code compliant) scenarios are given as occupant densities in Table 1. High occupancy was modeled for offices (twice the default office occupancy) such that the per-person rate would be the dominant driver of the prescribed MVR for the DCV strategies being assessed in this work. This high occupancy level modeled is representative of call centers, but not descriptive of most other office settings. Thus, the modeling results for offices show the upper limit of the potential energy savings and changes to IAQ in reference to the baseline. Occupancy densities for the retail building and schools were obtained from Title 24 mechanical compliance manual.

Empirical baseline MVRs (Table 1) were determined from literature indicating that office MVRs are commonly twice (200 percent) the rates prescribed in code (Mendell, Eliseeva et al. 2015), and that school MVRs are commonly 50 percent of Title 24 prescribed rates (Mendell, Eliseeva et al. 2013). There is insufficient data to determine empirical baseline MVR for retail buildings so it was not modeled.

5 A constant temperature set point was used to be constant with prior work (Dutton and Fisk, 2014). California’s Title 24 Standards recommend a lower set point for south coastal climate zones (6–9). It is likely that this study underestimated economizer use in those climate zones.

Table 1: Modeled Occupant Densities and Minimum Ventilation Rates in EnergyPlus

	Occupant Density	Floor Area-Based MVR	Occupancy-Based MVR	Baseline MVR	Empirical Baseline MVR
	m^2/person	m^3/s-m^2 (CFM/ft^2)	m^3/s-person (CFM/person)	m^3/s-m^2	m^3/s-m^2
Office	7.4	0.00076 (0.15)	0.00708 (15)	0.000955	0.00191
Retail	5.6	0.00102 (0.20)	0.00708 (15)	0.00127	NA
Primary/ Secondary School	3.7	0.00076 (0.15)	0.00708 (15)	0.00191	0.000955

Source: Lawrence Berkeley National Laboratory

Four DCV control strategies were modeled. Currently, Title 24 only permits CO_2-based DCV (DCV- CO_2). The other three (DCV-OCCUP, DCV-CONT, DCV-CONT-CO_2) are alternative control strategies modeled to see if very different energy savings and/or impacts on IAQ would result, compared with the currently code-compliant control strategy (DCV- CO_2).

1. DCV-CO_2 used the *IndoorAirQualityProcedure* specified as the *SystemOutdoorAirMethod* with an upper limit of 1,000 ppm. Modeled MVRs were maintained at or above the minimum floor area-based rate specified in Title 24 when the building is occupied.
2. DCV-OCCUP maintained the occupant-based MVR for each occupant in the room. When no occupants are present the VR is set to ¼ of the prescribed per floor area rate. There is no guidance pertaining to occupant count sensors in Title 24; however, there is guidance for MVR for zones controlled by occupancy sensors. The modeled control was based on the Title 24 2013 guidance[6] that states that when occupancy sensors indicate that the space is "vacant during hours of expected occupancy," the control should "maintain the average outdoor air rate over an averaging period of 120 minutes equal to 25 percent of the [prescribed per floor area rate]".
3. DCV-CONT used the *IndoorAirQualityProcedure-GenericContaminantOutdoorAir Method that* limits the indoor contaminant concentration to a hypothetical threshold (set to 0.04 ppm). Emission rates for the generic contaminant were

6 At the time this report was written, the authors expect that the ventilation rate requirement during vacant hours of expected occupancy will be simplified in the 2019 Title 24 standards.

calculated such that the steady state concentration of contaminant would meet this hypothetical threshold of 0.04 ppm under the Title 24 prescribed minimum VR, when this VR is based on the per floor area rate.

4. DCV-CONT-CO_2 was based on the DCV-CO_2**,** but with the addition of additional control that increased the VR if the generic contaminant concentration exceeded the threshold.

Full parametric simulations were performed for each of the control strategies in each climate zone and building type. State wide energy use, and IAQ metrics were calculated using the state wide averaging method outlined in (Benne, Griffith et al. 2009, Dutton and Fisk 2014).

Results

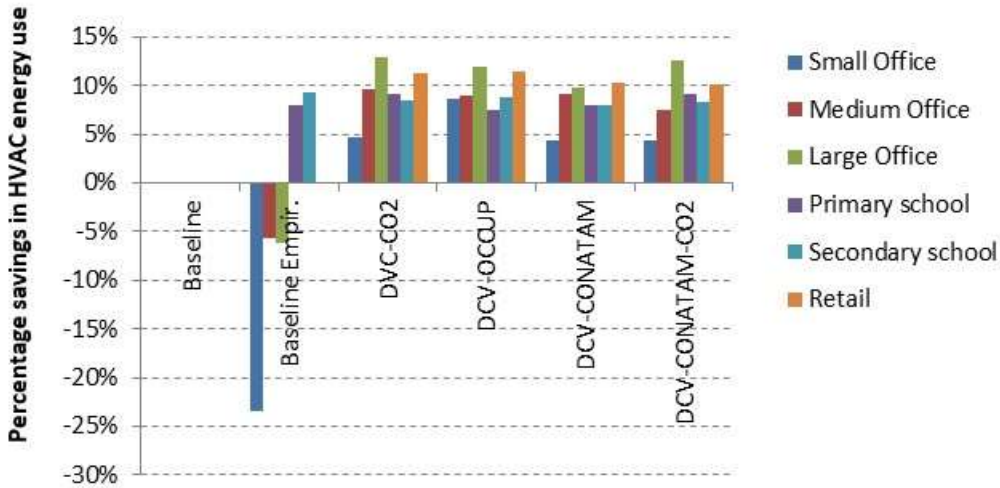
Heating, Ventilation, and Air Conditioning Energy Savings

Modeling results indicate large HVAC energy savings for all four DCV strategies in buildings with a high occupant density. Figure 6 shows the percentage savings in HVAC energy for each building type normalized to baseline, weighted by climate zone. Results show that, on average, the control strategies saved about 5 percent of the HVAC energy use for small office, and 8 percent to 13 percent for other building types. Savings varied considerably by climate zone and by building type. However, there was little variation in energy savings between the types of DCV strategies.

The energy savings for small, medium, and large offices using different DCV control strategies are the upper limits because they apply in cases when occupant density is very high, such as in call centers. Energy savings would be less for the general case where occupant density in offices is lower than modeled.

The greater VR in small offices for the baseline empirical scenario resulted in notable increases in HVAC energy use intensity, with the majority of the increases coming from increased heating energy use. Energy savings relative to the baseline case are highest for the small offices, probably because of the higher demand for heat in that building.

Figure 6: Statewide Average Percentage Savings in Heating, Ventilation, and Air Conditioning Energy



Energy savings normalized to baseline minimum ventilation rate scenario.

Source: Lawrence Berkeley National Laboratory

HVAC energy savings in offices were larger when buildings employing the DCV options were compared to buildings with baseline-empirical MVRs, which better represent actual practice. Maximum savings of 27 percent, 23 percent, and 30 percent were seen for the small, medium, and large offices, respectively, with high occupant density. Potential energy savings would be less for office buildings that have lower occupant density.

The HVAC energy savings in the primary and secondary schools when the reference buildings had Title 24 compliant MVRs were smaller, approximately 6 percent. With use of the DCV systems in schools, HVAC energy use is very similar to energy use in the baseline-empirical reference case with MVRs half of those specified in Title 24. This suggests an opportunity to improve indoor air quality in schools using DCV without using more energy compared to current practice.

The HVAC energy savings of the DCV strategies in the retail building were approximately 10 percent.

Figure 7 shows the impact of the various control strategies on end use components of the HVAC energy use for the small, medium, and large offices, the primary and secondary schools, and the retail building. The majority of these savings are reduced heating energy savings. This is consistent with prior studies that showed that reduced MVRs reduced heating energy use (Benne, Griffith et al. 2009, Dutton and Fisk 2014).

Figure 7: Impact of Different Demand-Controlled Ventilation Control Strategies on Heating, Ventilation, and Air Conditioning Energy Use Intensity

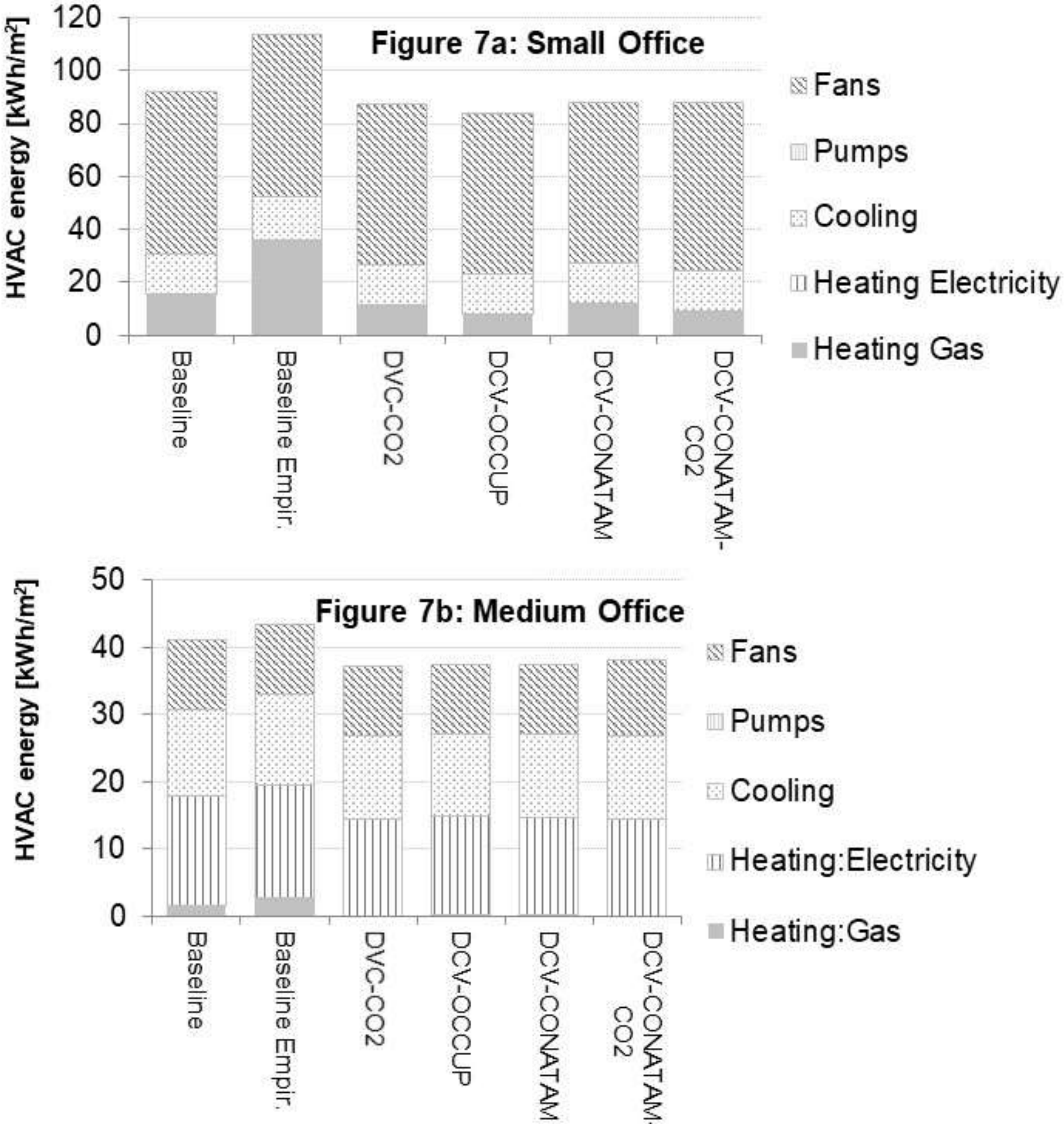
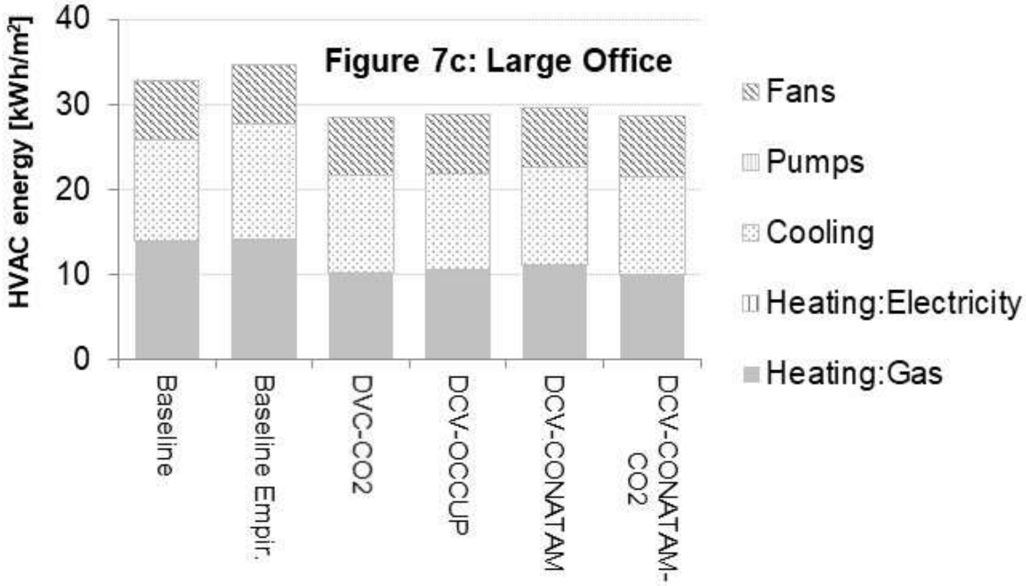


Figure 7 (cont'd): Impact of Different Demand-Controlled Ventilation Control Strategies on Heating, Ventilation, and Air Conditioning Energy Use Intensity



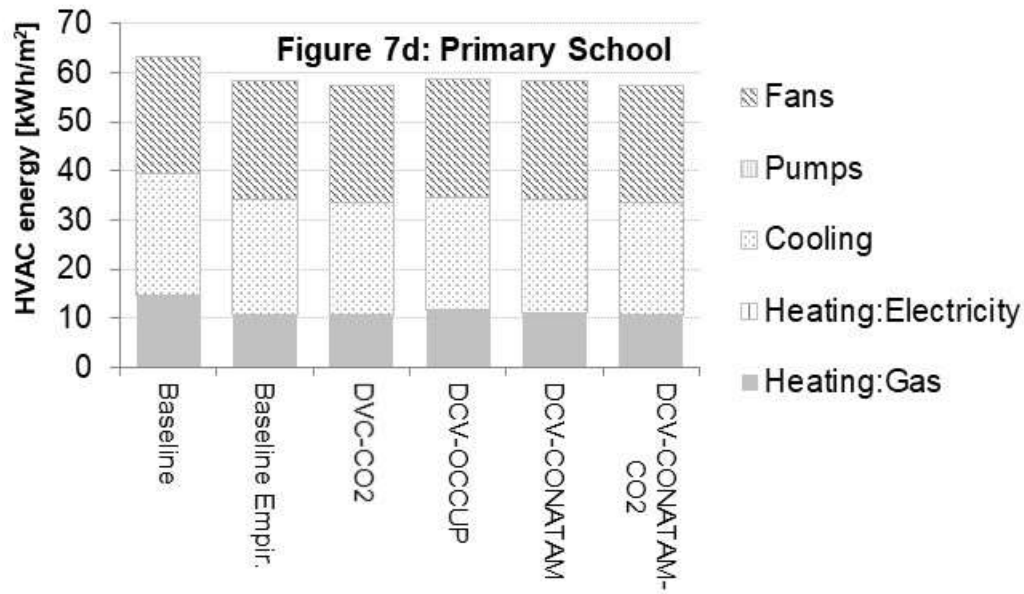
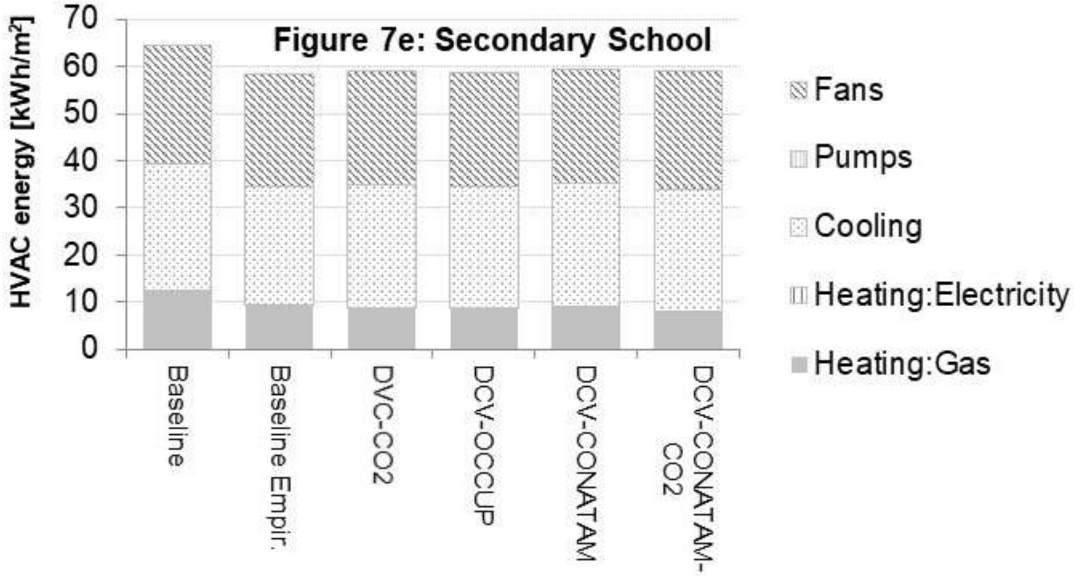
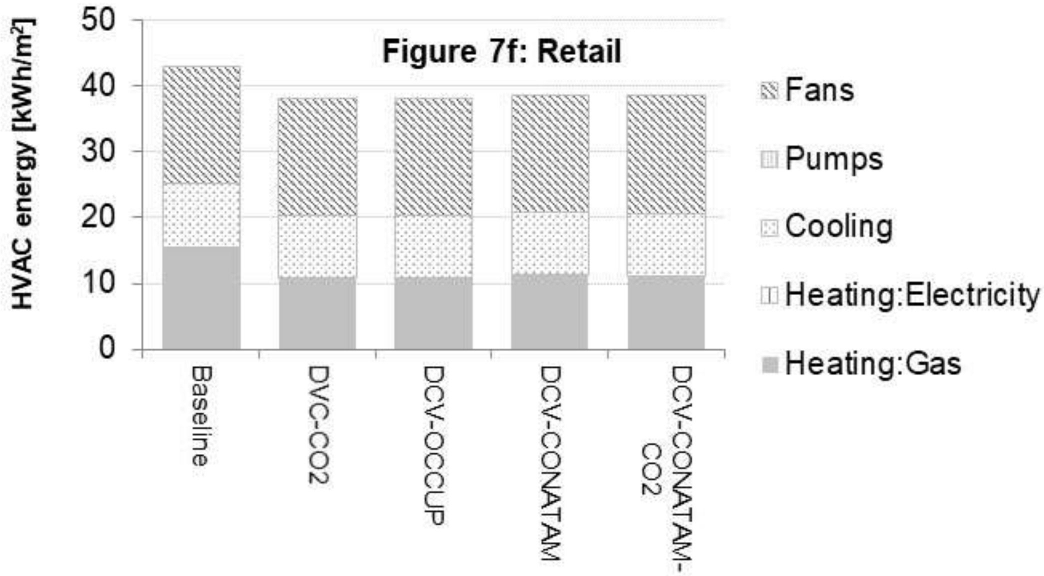


Figure 7 (cont'd): Impact of Different Demand-Controlled Ventilation Control Strategies on Heating, Ventilation, and Air Conditioning Energy Use Intensity





Source: Lawrence Berkeley National Laboratory

Results of the medium office show substantial electricity use for heating, which suggest that the United States Department of Energy reference building model (Griffith, Long et al. 2008) used in this analysis may not comply with Title 24. Despite this anomaly, the relative results comparing different DCV control strategies with respect to the code and empirical baseline for the medium office are similar to other building types modeled. Thus, the heavy use of reheating in the medium office, even though it is uncharacteristic of code-compliant California buildings, does not appear to meaningfully impact the overall finding of this study.

Impacts on Indoor Air Quality

Figure 8 shows the distributions of hourly average concentrations of CO_2, averaged for the whole building, during occupied periods. CO_2 concentrations were nearly always below the 1,000 ppm threshold. The results indicate that the exposure to CO_2 was, on average, not noticeably different between control strategies.

Peak hourly CO_2 concentrations in the small and medium office are above 1,000 ppm for a fraction of the time when the DCV-CONTAM control strategy is employed. This control strategy limits the indoor concentration of the generic contaminant, but does not constrain maximum CO_2 concentrations. Modeling results indicated lower CO_2 concentrations predicted when DCV control strategies are implemented, relative to the empirical baseline, in schools and offices.

Figure 8: Impact of Different Demand-controlled Ventilation Control Strategies on Carbon Dioxide Concentrations

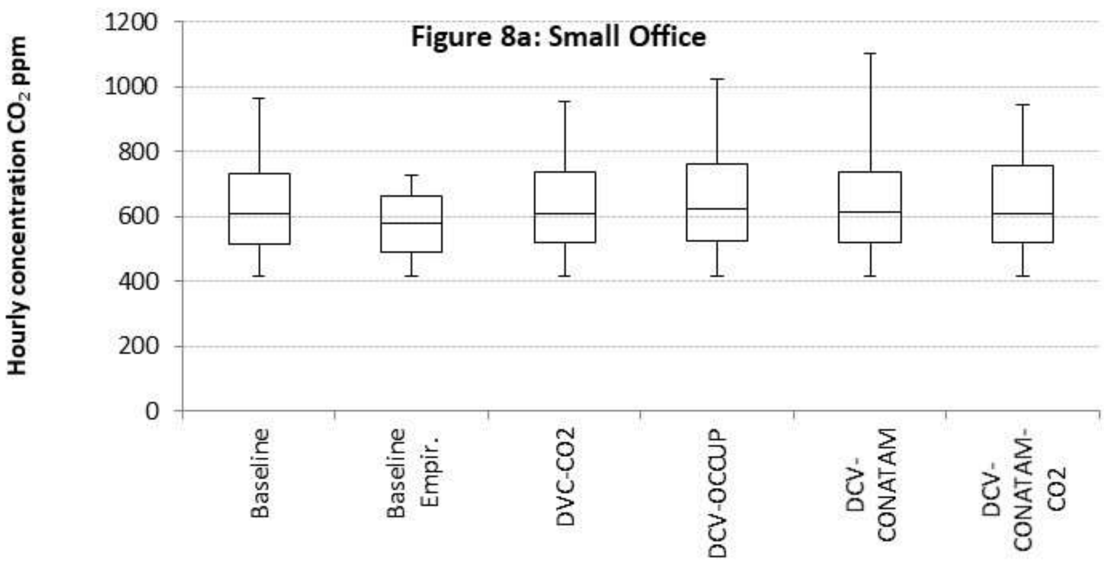
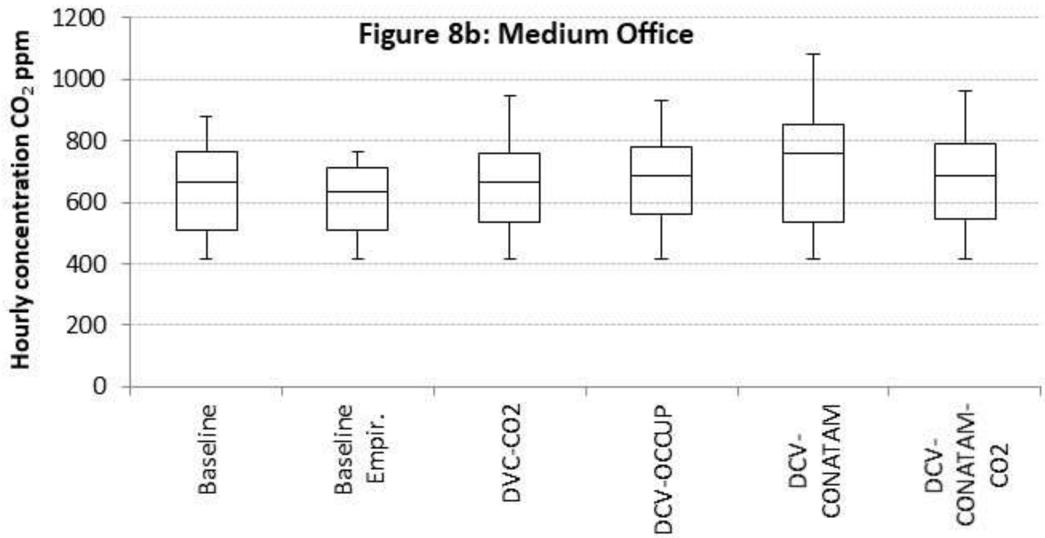


Figure 8 (cont'd): Impact of Different Demand-controlled Ventilation Control Strategies on Carbon Dioxide Concentrations



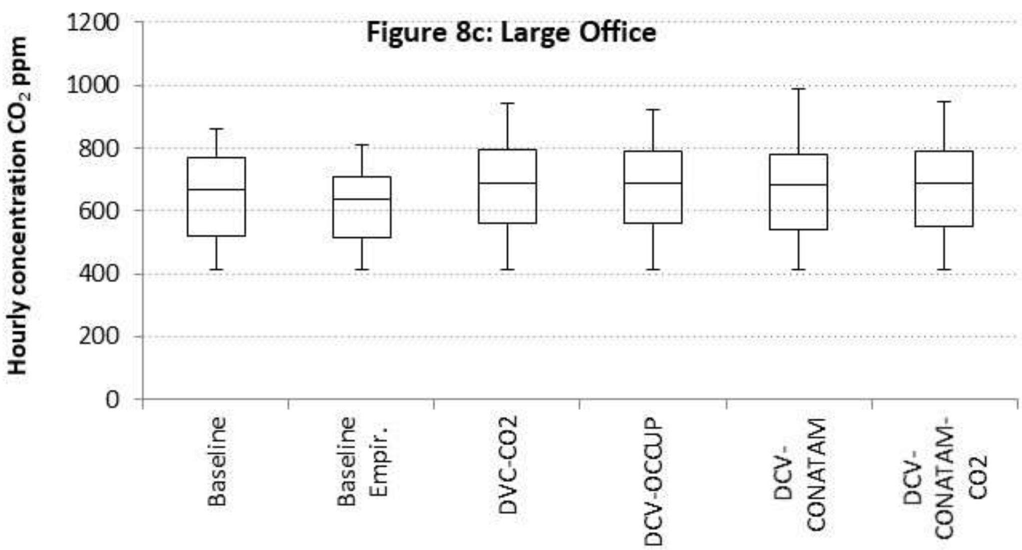
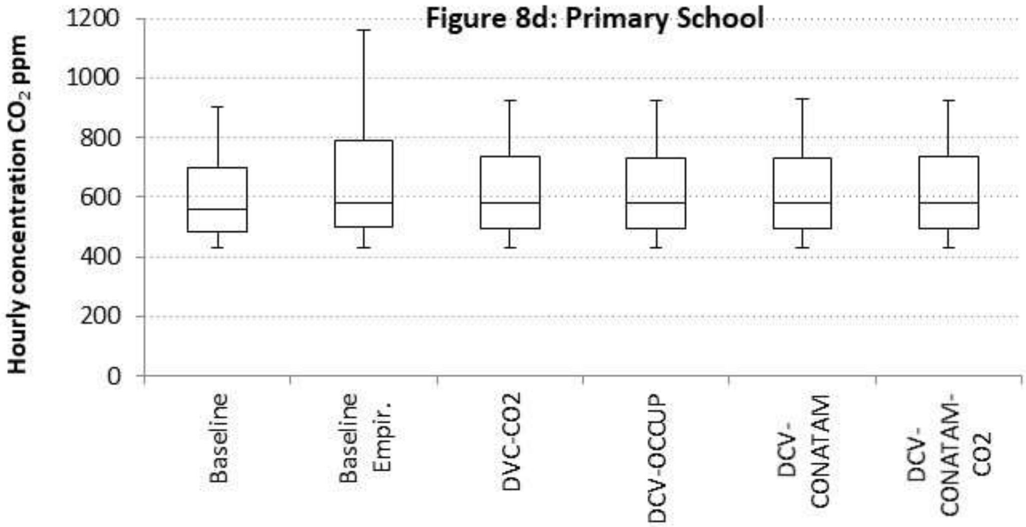


Figure 8 (cont'd): Impact of Different Demand-controlled Ventilation Control Strategies on Carbon Dioxide Concentrations



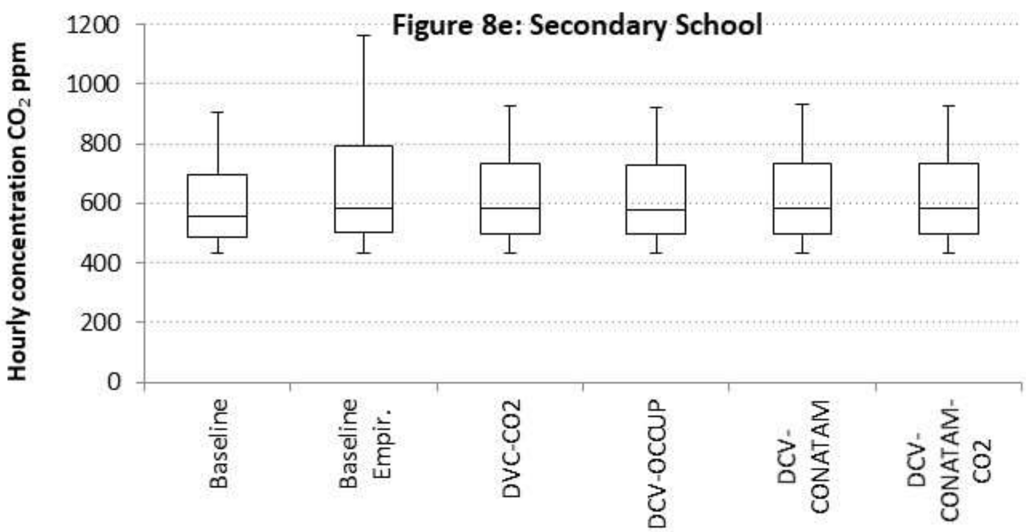
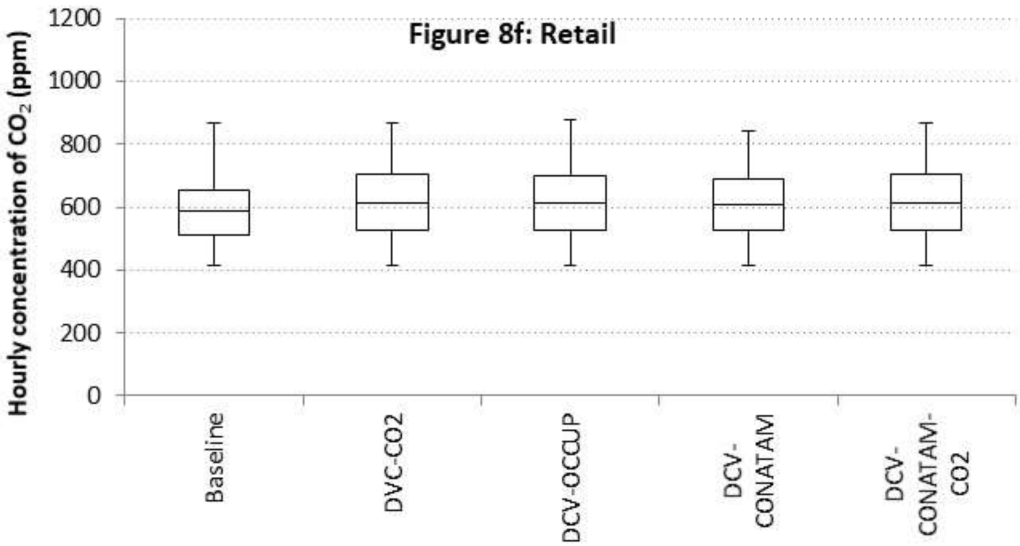


Figure 8 (cont'd): Impact of Different Demand-controlled Ventilation Control Strategies on Carbon Dioxide Concentrations



Box plot shows median, upper and lower inter-quartile, maximum and minimum values.

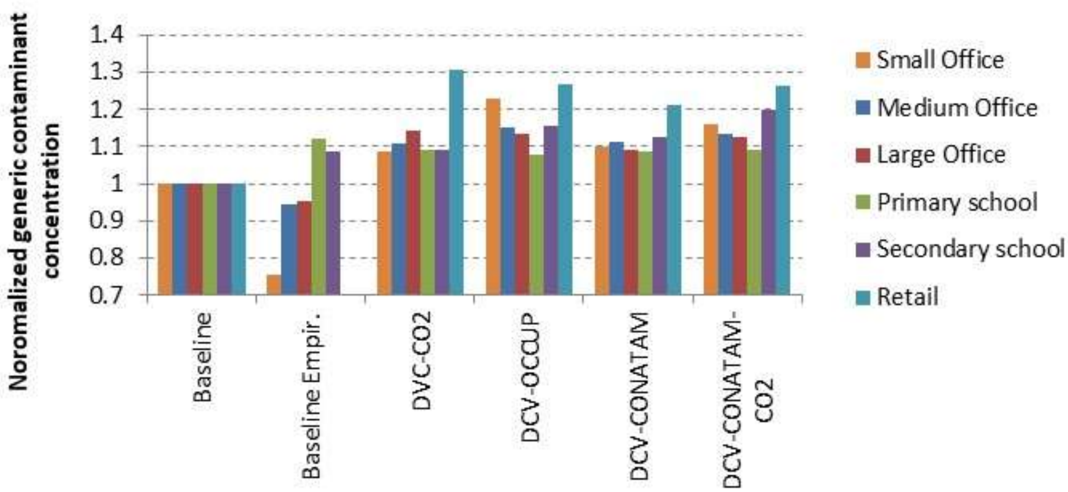
Source: Lawrence Berkeley National Laboratory

Figure 9 shows the statewide averages of mean generic contaminant concentrations predicted during occupied period. The research team observed some differences in the predicted mean generic contaminant concentrations with respect to the DCV control strategies being modeled. For the baseline case, all four DCV control strategies are expected to result in higher mean generic contaminant concentrations. This is because ventilation is reduced during hours when CO_2 or occupant count is low, so higher generic contaminant concentrations result when DCV- CO_2 and DCV-OCCUP is used. Similarly, ventilation is reduced for periods immediately following use of an economizer when generic contaminant concentrations have not yet accumulated to the hypothetical threshold of 0.04 ppm set under the Title 24 floor-area-based MVR. This reduction in ventilation means higher mean generic contaminant concentrations for DCV-CONTAM and DCV-CONTAM-CO2, as shown in Figure 9.

The slight increase in mean generic contaminant concentrations is a tradeoff of using DCV. These increases in concentrations are estimated to be around 10 percent or less for the medium and large offices and the primary, and secondary schools, 10 percent to 20 percent for the small office, and 20 percent to 30 percent for retail building. The concentrations were calculated for a constantly emitted contaminant such as formaldehyde, a contaminant constantly emitted from building materials and indoor furnishings. For the case of DCV-CO2 and DCV-OCCUP, because ventilation is reduced when there are fewer occupants, the overall change in total occupant-exposure to the generic contaminant is expected to be somewhat lower than the simple mean values shown in Figure 9 that were calculated irrespective of occupancy.

The slight increase in mean generic contaminant concentrations does not imply that DCV control strategies are unable to meet the 0.04 ppm hypothetical threshold that would be obtained with the fixed floor-area-based MVR specified in Title 24. In fact, generic contaminant concentrations were nearly always well below the 0.04 ppm value. Exceptions included exceedances of the 0.04 limit in the early morning when the purge had reduced the indoor generic contaminant concentrations appreciably but not to below the threshold. This suggests that buildings that use DCV need more purging compared to buildings without DCV to offset the accumulation of generic contaminant concentrations overnight.

Figure 9: Impact of Different Demand-Controlled Ventilation Control Strategies on Generic Contaminant Concentrations



Statewide averages of mean generic contaminant concentrations, normalized to the baseline scenario.

Source: Lawrence Berkeley National Laboratory

The baseline-empirical results show a decrease in generic contaminant concentration in offices, with respect to the baseline scenario. This is because offices are modeled to have higher MVRs from empirical data. On the other hand, schools show an increase in generic contaminant concentrations using MVRs from empirical data. The increase in generic contaminant concentrations was moderate in schools likely because of substantial economizer activation. In practice, many classrooms have packaged single-zone HVAC systems without a functioning economizer. In these classrooms, the low MVRs of the baseline-empirical scenario are expected to substantially increase concentrations of the generic contaminant more than is shown in Figure 9.

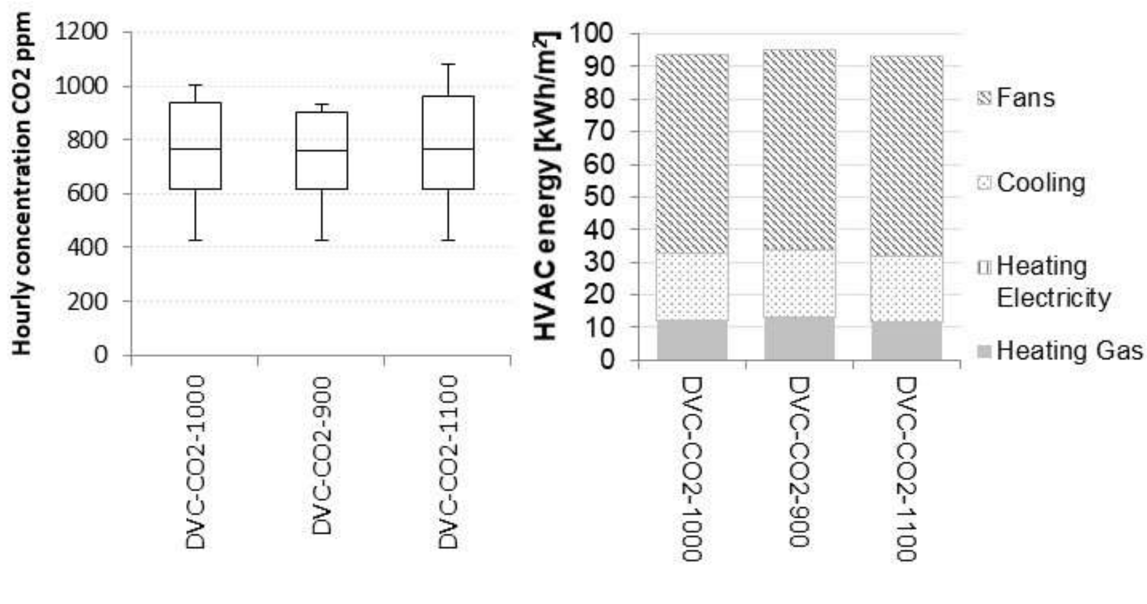
To summarize, the results show concentrations of CO_2 were nearly always below the 1,000 ppm threshold in all six buildings modeled, but peak CO_2 concentrations were marginally above 1,000 ppm when the DCV-CONTAM control strategy was employed.

Effects of Carbon Dioxide Sensor Errors

The team assessed the effects of small shifts in the CO_2 threshold (±100 ppm deviation from the 1,000 ppm set point) resulting from measurement errors of CO_2 sensors, using the small office building as an example. Model runs using initial occupancy of 7.4 m^2/person resulted in very few hours of indoor CO_2 concentrations exceeding 1,000 ppm. For this comparison, the occupancy of the small office was doubled (i.e., from 7.4 m^2/person to 3.7 m^2/person) to illustrate the effects of CO_2 sensor errors on indoor CO_2 concentrations and HVAC energy use.

Figure 10 shows that when the sensor underestimates CO_2 concentration by 100 ppm (the sensor reads 1,000 ppm but the actual concentration is 1,100 ppm, labeled DCV-CO2-1100 in Figure 10), the mean CO_2 concentration during occupied periods (weighted by climate zone) increased by approximately 3 percent and HVAC energy use decreased by 0.6 percent. Control variant DCV-CO2-900 represents an overestimation of CO_2, resulting in a 4 percent decrease in average CO_2 concentration during occupancy and a 1.3 percent increase in energy use compared to the DCV-CO2-1000 case.

Figure 10: Effect of Carbon Dioxide Sensor Measurement Errors



Statewide results using small office as an example to show effects of CO_2 sensor measurement error (±100 ppm deviation from 1,000 ppm set point). Box plot shows median, upper and lower inter-quartile, maximum and minimum values.

Source: Lawrence Berkeley National Laboratory

Discussion

DCV strategies reduce MVRs during periods of either reduced occupancy or when the IAQ in space allows for reduced MVR. Energy savings from DCV are seen immediately following either a period of economizer operation or in the morning following the preoccupancy purge, where DCV based MVRs are allowed to fall below the prescribed minimum MVRs for HVAC systems without economizers. The predicted energy savings were about 5 percent for small office, and 8 percent to 13 percent for other building types. These energy savings are closely related to the reduction in average VRs during periods when the economizer is off. The savings projected for offices would be much less if the occupant density was lower than the high rates of occupant density modeled in this study. Also, the energy savings of DCV strategies will depend on the MVR specifications of the applicable standard. The MVR per floor area requirements of Title 24 limit the energy savings of DCV in offices, unless occupant densities are high.

In this analysis, DCV strategies are implemented only when the economizer is not activated. The use of economizers has an appreciable impact on potential energy savings of reducing prescribed minimum VRs (Dutton and Fisk 2014). Lacking data on what economizer set points are used in California commercial buildings, the economizer control strategy used in this study was based on prior modeling efforts and anecdotal evidence of typical set points. Recent automated fault detection and diagnostics requirements in Title 24 likely have improved compliance on the proper use of economizer set points. The *Maximum Limit Dry-Bulb Temperature* set point limits economizer operation to periods where outside dry bulb air temperatures are below the set point. Shifting this value would change the proportion of occupied time when DCV is active, such as in south coastal climate zones where Title 24 specifies lower temperature set points below the 24^{o}C used in this analysis, and would also shift the impact those strategies have on energy consumption and indoor contaminant concentrations.

Results of this study suggest that retrofitting schools with DCV could reduce exposure to contaminants, if, as is often the case, the school had been operating with below-prescribed MVR before the retrofit. These benefits would be greatest in climates that use economizers less often. Results shown in Figure 7 (see 7d for primary school and 7e for secondary school) further suggest that reductions in CO_2 and generic contaminant concentrations can be achieved without using more HVAC energy than current practices, if DCV is used.

Empirical data indicate low VRs and high CO_2 concentrations in many of California's classrooms, with CO_2 concentrations sometimes exceeding 3,000 ppm (Mendell, Eliseeva et al. 2013) and VRs less than 25 percent of Title 24 prescribed MVRs. In contrast, the modeling indicates only moderate increases in CO_2 concentrations for the baseline-empirical reference case. This discrepancy is likely due to differences between the modeled schools, which had economizers, and the schools in which actual CO_2 concentrations have been measured, which generally had no economizers. In schools without economizers, one would expect DCV to reduce CO_2 and generic contaminant concentrations by substantially more than indicated by this study's simulations with respect to the empirical reference case.

In small offices, the predicted change in generic contaminant concentrations was 10 percent to 20 percent compared to the baseline. Further analysis of small office buildings is needed to determine if such increases in generic contaminant concentrations would adversely affect occupant health and satisfaction. The predicted change in generic contaminant concentrations in retail buildings (20 percent to 30 percent with respect to baseline) when DCV strategies were used should also be considered for its potential effect on occupants. In other building types (medium and large offices, primary and secondary schools), the change in generic contaminant concentrations is small (about 10 percent or less).

Substantial energy savings could be realized by avoiding over-ventilation in buildings. One could argue that these savings would be realized anyway if commissioning of the HVAC system established the prescribed MVR. A counterpoint is that in practice, offices may be unlikely to make changes to the HVAC system unless some sort of retrofit is performed. A second point to consider is that commercial HVAC systems are complex and the provision of outside air ventilation is sensitive to factors that change over time, such as internal changes in the building such as doors being closed or remodeling, and variable air volume control sequence. Also, accurate measurements of VRs are technically challenging. Thus, even without changes over time, MVRs may be incorrectly set. Data on CO_2, assuming it is measured accurately, offers one method of correcting for changes in system performance or inaccurate MVR set points while attempting to maintain established IAQ goals.

A sensitivity study was used to investigate the impact of a fixed offset in CO_2 sensor accuracy. The results showed that a 100-ppm shift in sensor accuracy, in either the positive or negative direction, affected time-average CO_2 concentrations during occupancy less than 5 percent. The majority of the energy savings from employing CO_2 sensor based DCV were maintained, even when the CO_2 sensors greatly overestimated the indoor CO_2 concentration. However, in buildings where CO_2 sensors are more inaccurate than is modeled here (for example, Fisk, Sullivan et al. (2010) found 31 percent of CO_2 sensors used in commercial buildings have errors greater than +/- 100 ppm), the deviation in expected energy savings from DCV will be larger.

Conclusions

Applied statewide, DCV in the simulated buildings would be expected to deliver a comparable 10 percent savings in California. The majority of the HVAC energy savings were related to reduced heating energy use. In climates where economizer use is less extensive, these savings would be larger. The modeled buildings had HVAC systems with economizers, and larger effects would be anticipated where HVAC systems had no economizers.

Applying MVR based on empirical data showed that application of DCV would have saved significantly more energy if the buildings to which it was applied were overventilating before the application of DCV.

DCV increased concentrations of the generic contaminant in offices when the reference building had the baseline empirical MVRs. In contrast, DCV decreased concentrations of the generic contaminant in schools when the reference building had the baseline empirical MVRs. However, effects were modest because of the large fraction of time that economizers were activated.

Concentrations of CO_2 were nearly always below the 1,000 ppm threshold, in all six buildings modeled. A 100-ppm error in CO_2 sensor readings did not appreciably diminish the savings realized by employing CO_2 based DCV.

Evaluation of Commercially Available Technologies for Measuring Outside Air Intake Flow Rates

Objectives

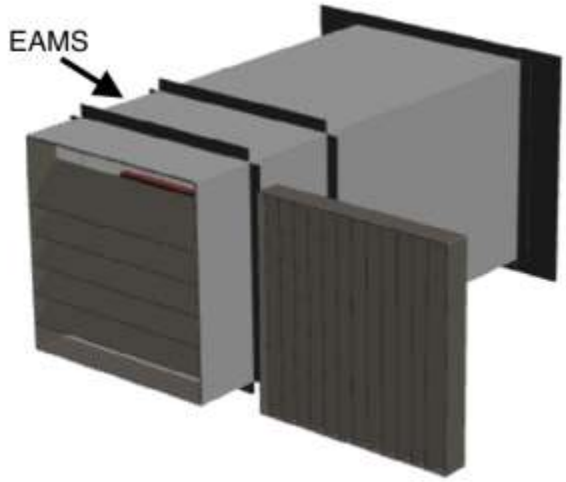
This component of the research evaluated the accuracy of two commercially available outdoor airflow measurement technologies (OAMTs) marketed for measurement and control of rates of outdoor airflow into air handlers. The two systems were evaluated for measurement accuracy using a unique test system located on a building rooftop. Measurement of outdoor airflow intake rates is technically challenging in most air handling systems because of the complex airflow patterns and limited space upstream of where outdoor air and recirculated indoor air is mixed. Low air velocities when MVRs are supplied in HVAC systems with economizers is another factor that causes difficulties with accurate measurement.

Methods

The team evaluated two commercially available OAMTs, the Ruskin Electronic Air Measuring Station (EAMS) and the Ebtron Gold probe system. The Ebtron system contained two probes, each with three velocity sensors. The two OAMTs were selected for evaluation in consultation with members of the Technical Advisory Committee for the project. The Ruskin EAMS was tested with an upstream vertical-blade louver and a horizontal-blade louver and was installed per manufacturer's guidance (Figure 11). The two louvers were purchased from Ruskin.

The Ebtron Gold probe system was tested with two typical air intake hood designs and installed per manufacturer's guidance (Figure 12). Prior work (Fisk, Cohen et al. 2008) tested the performance of Ebtron velocity probes installed downstream of various types of louvers. Measurement accuracy was sometimes poor because of non-uniform velocity profile. The use of air intake hood in this study may provide more uniform velocity profile.

Figure 11: Electronic Air Measuring Station Installation with an Upstream Louver



EAMS installation shown with a horizontal-blade louver. The vertical-blade louver is shown on the side.

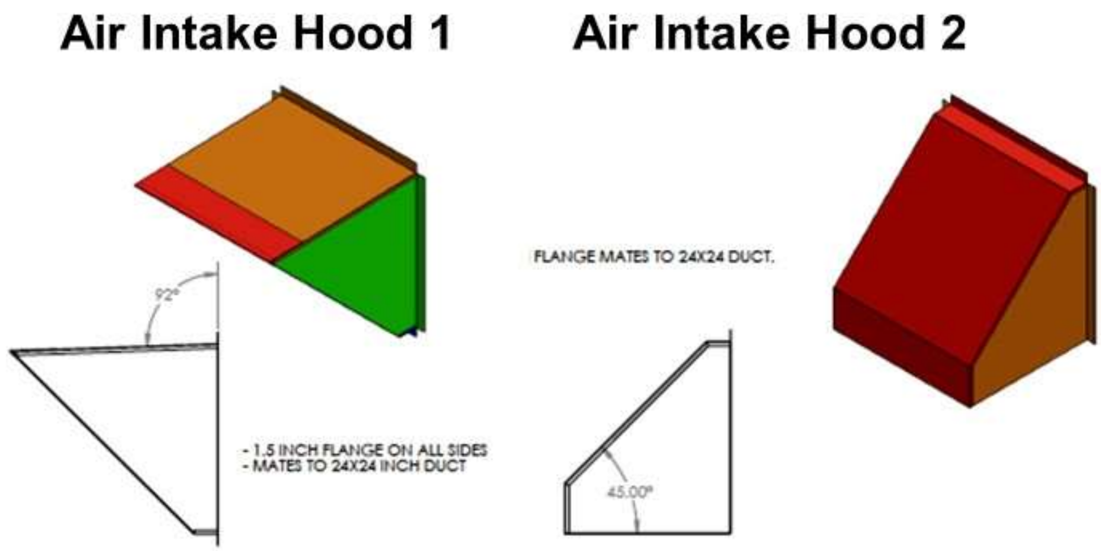
Source: Lawrence Berkeley National Laboratory

Per manufacturer's guidance, the EAMS should be installed at least 10 cm (four inches) downstream of a louver and one hydraulic diameter upstream of the outdoor air (OA) damper. If one uses the EAMS with a louver that functions at high air speeds, such as the Ruskin EME3625[7] vertical-blade louver with a maximum nominal velocity downstream of the louver of 3.2 m s^{-1} (630 fpm), the velocity specifications of the EAMS indicate that the OA airflow can be measured over a range from 15 percent to 100 percent of the supply airflow. If one uses a more typical horizontal blade louver, such as the Ruskin 375DX[8] with a maximum nominal velocity downstream of the louver of 2.4 m s^{-1} (470 fpm), the velocity specifications indicate that the outdoor airflow can be measured over a somewhat narrower range from 21 percent to 100 percent of the supply airflow.

7 Ruskin EME3625 (http://www.ruskin.com/file/model/EME3625/doc/2258).

8 Ruskin 375DX (http://www.ruskin.com/file/model/ELF375DX/doc/318).

Figure 12: Air Intake Hoods Tested with Ebtron Gold Probe System



Source: Lawrence Berkeley National Laboratory

The outlet of the air intake hoods and the section of duct containing the Ebtron probes had dimensions of 0.61 m by 0.61 m (24 inch by 24 inch). The Ebtron probes were installed per manufacturer's guidance: at least 30.5 cm (12 inches) downstream of a louver, at least 15.2 cm (6 inches) downstream of the outlet plane of an air intake hood, at least 15.2 cm (6 inches) upstream of the upstream edge of OA damper blades when the damper is open. The manufacturer indicates[9] that the Ebtron Gold system is usable for air velocities of 0 m s^{-1} to 25.4 m s^{-1} (0 to 5,000 fpm).

Evaluation System

Because it is very challenging to reproduce variable weather conditions in a laboratory, the OAMTs were evaluated using a unique test system on the rooftop of a building on LBNL campus. Wind, with temporal changes in both speed and direction, may influence the air speeds and static pressures at the OA intake of an HVAC system and the accuracy of OAMTs. The temperature and humidity of OA entering HVAC systems will vary depending on the local weather conditions and may also affect accuracy. In periods with precipitation or fog, small suspended water droplets may be carried into the RTU by the OA, possibly affecting velocity sensor accuracy.

Figure 13 shows a top-view schematic of the main features of the evaluation system. The evaluation system has a maximum flow rate of approximately 1,000 liters per second (2,100 cubic feet per minute [cfm], or 2.7 m s^{-1} with a 24″x24″ inlet), typical of a rooftop unit with a 20kW (6 ton) of refrigeration capacity.

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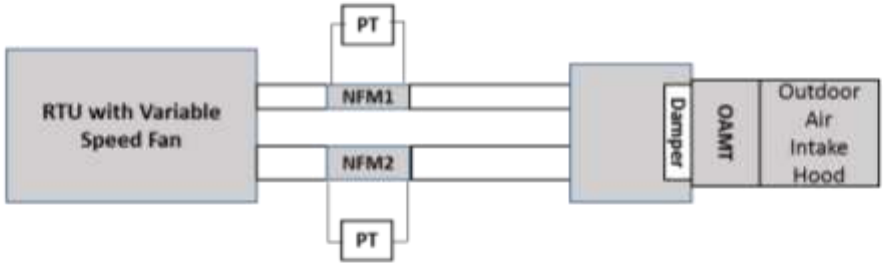
9 Ebtron Gold System (https://ebtron.com/wp-content/uploads/documents/IG_P_INS.pdf, https://ebtron.com/wp-content/uploads/documents/IG_GTC116.pdf).

Figure 13: Evaluation System for Testing Outside Airflow Measurement Technology Accuracy



NFM1 and NFM2 are different size nozzle flow meters. PT is a pressure transducer.

Source: Lawrence Berkeley National Laboratory

Measurement errors of OAMTs were computed with respect to a reference airflow meter, which is composed of a pair of different size nozzle airflow meters (NFM1 and NFM2, Thermo-Brandt Instruments NZP-1031 6" and 12") with upstream honeycomb airflow straighteners, connected to research-grade pressure transducers (Energy Conservatory APT-3-8). Researchers estimated a total uncertainty of 5 percent for the reference measurements of outdoor airflow rates. Sections of straight pipe upstream and downstream of the nozzle flow meters are provided in accordance with the manufacturer's specifications. Plates can be installed to prevent airflow through either nozzle flow meter, so that airflow can be measured using either the smaller, larger, or both nozzle flow meters, enabling the flow rates through the airflow meters to be maintained in the range that produces a pressure signal of sufficient magnitude for accurate measurement. A weather station (Davis Instruments Vantage Vue wireless) located 3 m (10 ft.) above the rooftop, measures wind speed, wind direction, temperature, humidity, and atmospheric pressure.

Evaluation Protocol

Two types of evaluations were performed. First, for each hardware configuration (that is, OAMT type, louver type or air intake hood, and outdoor air damper position at 25 percent, 75 percent, or 100 percent open), the rate of outdoor airflow rate was varied by changing the fan speed and by opening or blocking airflow through the nozzle air flow meters (NFMs) as needed to maintain pressure signals greater than approximately 16 Pascals (Pa) (0.064 inch water). The resulting flow rates tested ranged between 100 to 1,000 L s^{-1}, i.e. 10 percent to 100 percent of the maximum flow rate. Each flow rate was held constant for approximately 60 minutes. To the extent possible, tests were performed when wind speeds were low, e.g., 2 to 3 m s^{-1} or lower.

The measurement errors of the OAMTs were computed as follows:

$$Error = (F_{OAMT} - F_{REF})/F_{REF}$$

where F_{OAMT} is the air flow rate measured by the OAMT systems, and F_{REF} is flow rate indicated by the reference nozzle airflow meter(s).

In the second type of evaluation, the systems were operated for approximately two weeks with fixed hardware configurations and outdoor airflow rate while wind speed, wind direction, and outdoor temperature and humidity varied naturally. The primary purpose of these longer-term experiments was to determine the extent to which wind conditions affected the accuracy of the OAMTs. Trends in errors with air temperature and relative humidity were also assessed.

Results

Experiments were conducted between September and December 2015. Over a range of face velocities varying between 0.3 and 3 m s^{-1}, the accuracy of the OAMTs (Table 2 and Table 3) was in the 3 percent to 5 percent range, as specified by manufacturers, only at the higher end of the velocity range. Results of EAMS testing were shown only for velocity greater than 0.5 m s^{-1}, which is the lower limit recommended by the manufacturer. At the lower velocities that may be required to measure minimum outdoor air in HVAC systems with economizers, both OAMTs showed substantial measurement errors compared to the reference airflow meter.

Table 2: Accuracy of Ruskin Electronic Air Measuring Station

Approx. % of Max. Outdoor Air Flow	VL Ref. Face Velocity (m s^{-1})	VL Avg. Error	HL Ref. Face Velocity (m s^{-1})	HL Avg. Error
10%	—	—	—	—
20%	0.5	12%	0.6	-27%
30%	0.9	37%	0.9	-7%
45%	1.3	37%	1.3	-2%
75%	2.1	35%	2.0	2%
100%	2.9	31%	2.8	1%

VL = vertical louver; HL = horizontal louver. Results of EAMS testing were shown only for velocity >0.5 m s^{-1}, which is the lower limit recommended by the manufacturer.

Source: Lawrence Berkeley National Laboratory

Table 3: Accuracy of Ebtron Gold Probe System

Approx. % of Max. Outdoor Air Flow	AIH1 Ref. Face Velocity ($m\ s^{-1}$)	AIH1 Avg. Error	AIH1 Ref. Face Velocity ($m\ s^{-1}$)	AIH2 Avg. Error
10%	0.3	50%	0.3	80%
20%	0.5	22%	0.6	46%
30%	0.9	20%	0.9	30%
45%	1.4	10%	1.3	21%
75%	2.2	3%	2.1	12%
100%	3.0	-6%	2.9	5%

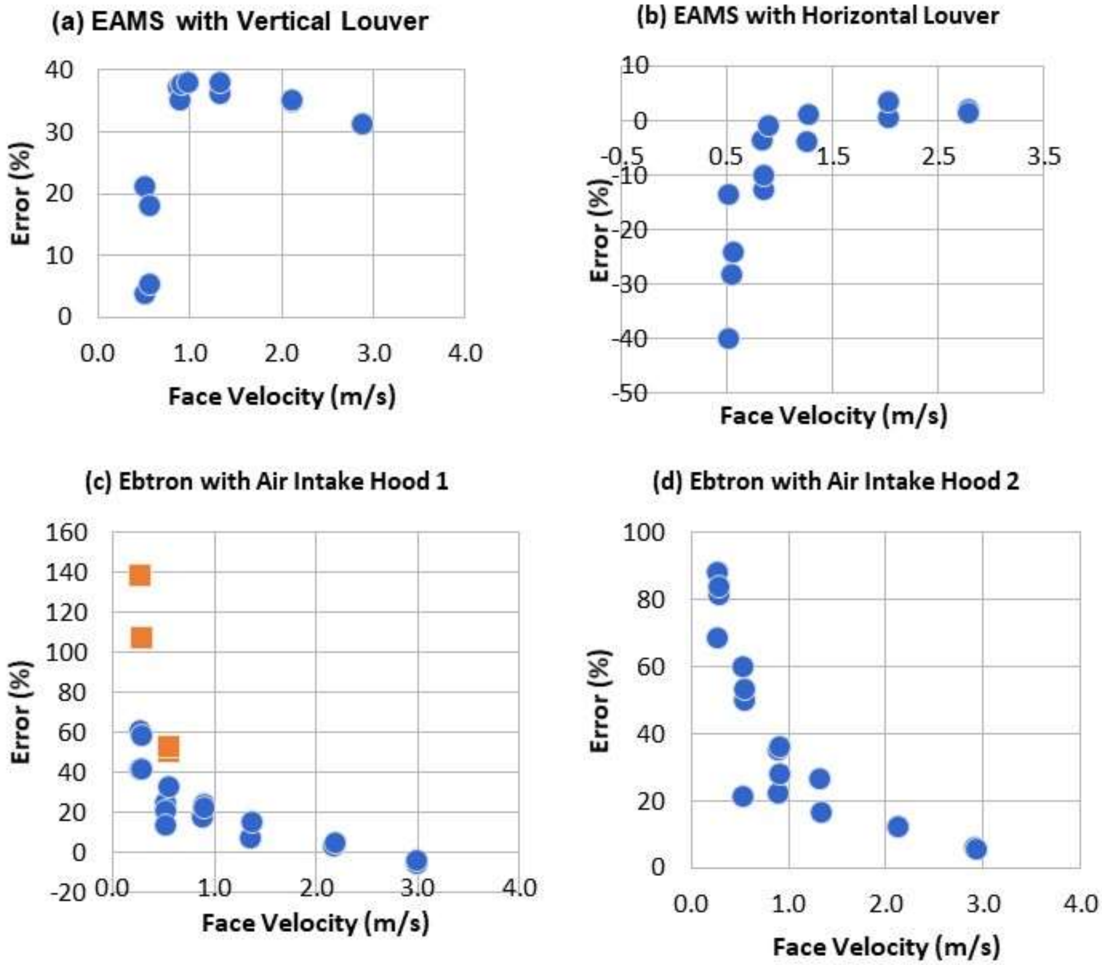
AIH1 = air intake hood 1; AIH2 = air intake hood 2.

Source: Lawrence Berkeley National Laboratory

The accuracy of the EAMS depended on the type of upstream louver. When tested with a horizontal-blade louver, measurements by the EAMS were about 25 percent below the reference method at the lower velocity limit of 0.5 $m\ s^{-1}$. At velocity of 1 $m\ s^{-1}$ and higher, measurement error approached the ± 3 percent accuracy reported by the manufacturer. When the EAMS was tested with a vertical-blade louver, the airflow rates measured by the EAMS had an error of 30 percent to 40 percent at a face velocity of 1 $m\ s^{-1}$ and higher. This systemic over-reporting of airflow rates was not observed when the EAMS was tested with a horizontal-blade louver.

On average, lower measurement errors were observed with the Ebtron Gold probe system when it was tested with air intake hood 1, compared to hood 2. The shape of hood 1 enables a straighter airflow path than hood 2, this may explain the lower measurement errors with the Ebtron Gold probe system tested with hood 1. However, the Ebtron Gold probes were more exposed to the wind when tested with hood 1. Consequently, when face velocities were below 0.5 $m\ s^{-1}$ larger measurement errors were observed at higher wind speeds. This result can be seen in the square red data points of Figure 14 (c), which represent data taken when wind speeds exceeded 4 $m\ s^{-1}$.

Figure 14: Outside Airflow Measurement Technologies Measurement Errors as a Function of Face Velocity



Measurement error of (c) Ebtron Gold probe system tested with air intake hood 1, during periods of high wind (>4 m s^{-1}, indicated in red squares) were excluded from the calculation of average percent error in Table 2.

Source: Lawrence Berkeley National Laboratory

Measured Pressure Drops

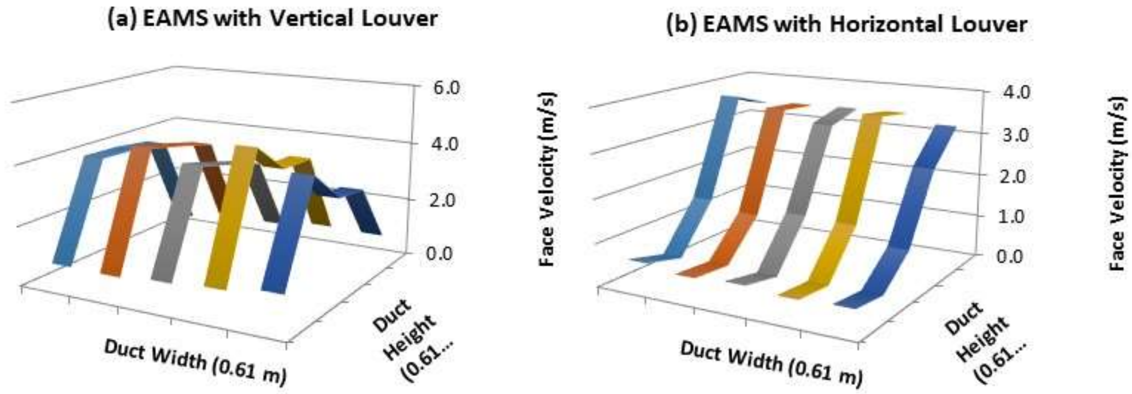
The air intake hoods used with the Ebtron Gold probe system introduced a small pressure drop of approximately 15 Pa (hood 1) and 30 Pa (hood 2) at the maximum airflow rate (see Appendix B). This was measured using a multi-channel pressure transducer via pressure taps at three locations of the duct (top and the two sides) immediate downstream of the Ebtron probe. For the EAMS installation, direct measurement of pressure drop is not practical because of the complex airflow between the outlet of the louver and the inlet of the OA flow control damper. Thus, at maximum airflow rates the pressure drops downstream of the EAMS plus louvers were measured and compared to the manufacturers' reported louver pressure drops of between 60 and 70 Pa for both louvers[2,3] at the same airflow rates. The measured pressure drops were

60 Pa for the EAMS plus horizontal louver and 110 Pa for the EAMS plus vertical louver at the maximum airflow rate. Thus, the measured pressure drop with the horizontal-blade louver matched the pressure drop specified by the louver manufacturer, indicating a negligible incremental pressure drop for the EAMS system. In contrast, the measured pressure drop with the vertical-blade louver exceeded the pressure drop specified by the louver manufacturer, suggesting a substantial incremental pressure drop imposed by the EAMS system. There is no reason to expect a dramatically higher pressure drop from the EAMS with an upstream vertical-blade louver. Possibly, the manufacturer's specified pressure drop for the vertical louver assumes a larger louver with less edge effects. Based on the moderate area of airflow obstructed by the EAMS, the system is expected to impose a small pressure drop; however, the testing was not able to quantify this pressure drop.

Velocity Profile Upstream of Electronic Air Measuring Station

To determine the cause of meaningfully different errors of the EAMS measured with the vertical-blade and horizontal-blade louvers, the air velocity profile in the duct immediately upstream of the EAMS was measured using a hot wire anemometer. The results of a traverse with velocities measured at 25 points (5 points across the width and 5 points across the height of the 0.61 m by 0.61 m (2 ft by 2 ft) duct, see Figure 15) show very different air velocity profiles between the two louvers. Neither showed uniform air speed. The vertical-blade louver resulted in low velocities near the top and bottom of the duct, possibly because of blocking of airflow by the frame of the louver. If the EAMS measured air velocities mostly at the mid-height of the duct, this would explain the over-reporting of airflows by the EAMS. The horizontal-blade louver directed air upwards, resulting in low velocities near the bottom of the duct, and high velocities hear the top of the duct. If the EAMS measured air velocities mostly at the mid-height of the duct, it would report air velocities closer to the reference value when used with the horizontal blade louver.

Figure 15: Velocity Profile Measured Upstream of Electronic Air Measurement Station



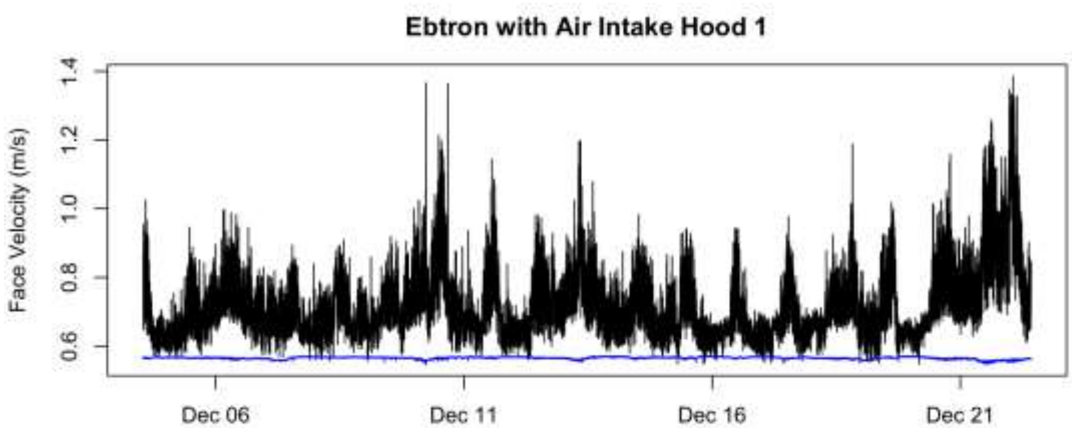
Velocity profile measured at distances 4.5, 17.6, 30.5, 43.4, and 56.6 cm from the top left corner of the 0,61 m by 0.61 m (2 ft by 2 ft) duct. The average face velocity was 2.6 m s^{-1} measured with the vertical louver (top) and 1.7 m s^{-1} measured with the horizontal louver (bottom).

Source: Lawrence Berkeley National Laboratory

Sensitivity to Weather Conditions

The Ebtron Gold probe system installed with air intake hood 1 showed the most sensitivity to weather conditions. Figure 16 shows measurements by the Ebtron system varied between 0.6 and 1.2 m s^{-1} over a two-week period, where the reference airflow meter indicated a constant 0.6 m s^{-1}. This and all subsequent analyses of longer-term experiments were performed using 10-minute running averages of airflow measurements and weather data, to reduce noise in the data so that trends can be more easily observed.

Figure 16: Two-Week Measurements by Ebtron Gold Probe System



Reference measurements by airflow meter shown in blue for comparison.

Source: Lawrence Berkeley National Laboratory

Figure 17 shows the measurement errors as a function of wind directions and wind speeds, when wind was blowing from between 105 and 165 degrees, from between 205 and 295 degrees, and from all other directions. The Ebtron Gold probe system had measurement errors in the range of 10 percent to 20 percent when not impacted by wind. The air intake faces approximately south, thus wind from the directions identified were directed towards the air inlet. Measurement errors increased with wind speeds, especially when wind was from between 205 and 295 degrees. At 6 m s^{-1}, wind from between 205 and 295 degrees would cause measurement errors to approach 80 percent.

Figure 17: Effects of Wind on Measurement Error of Ebtron Gold Probe System Tested with Air Intake Hood 1

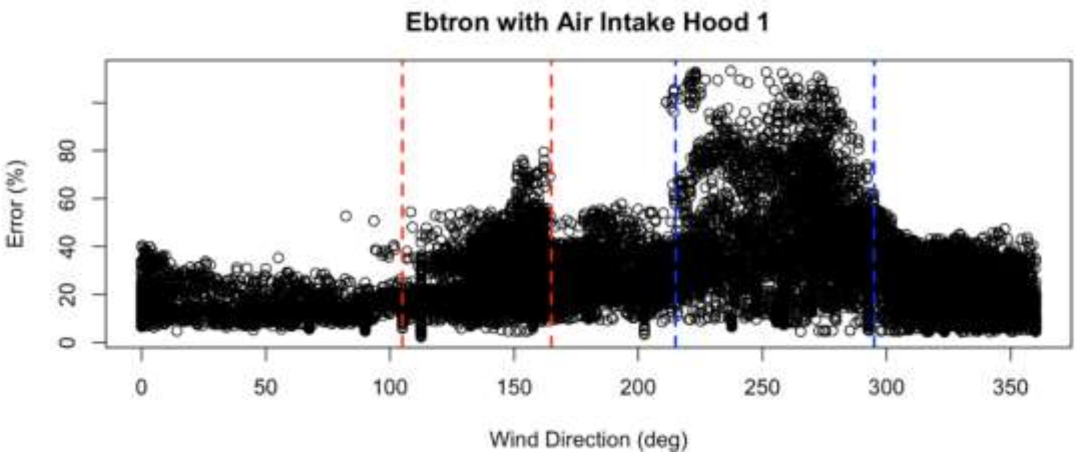
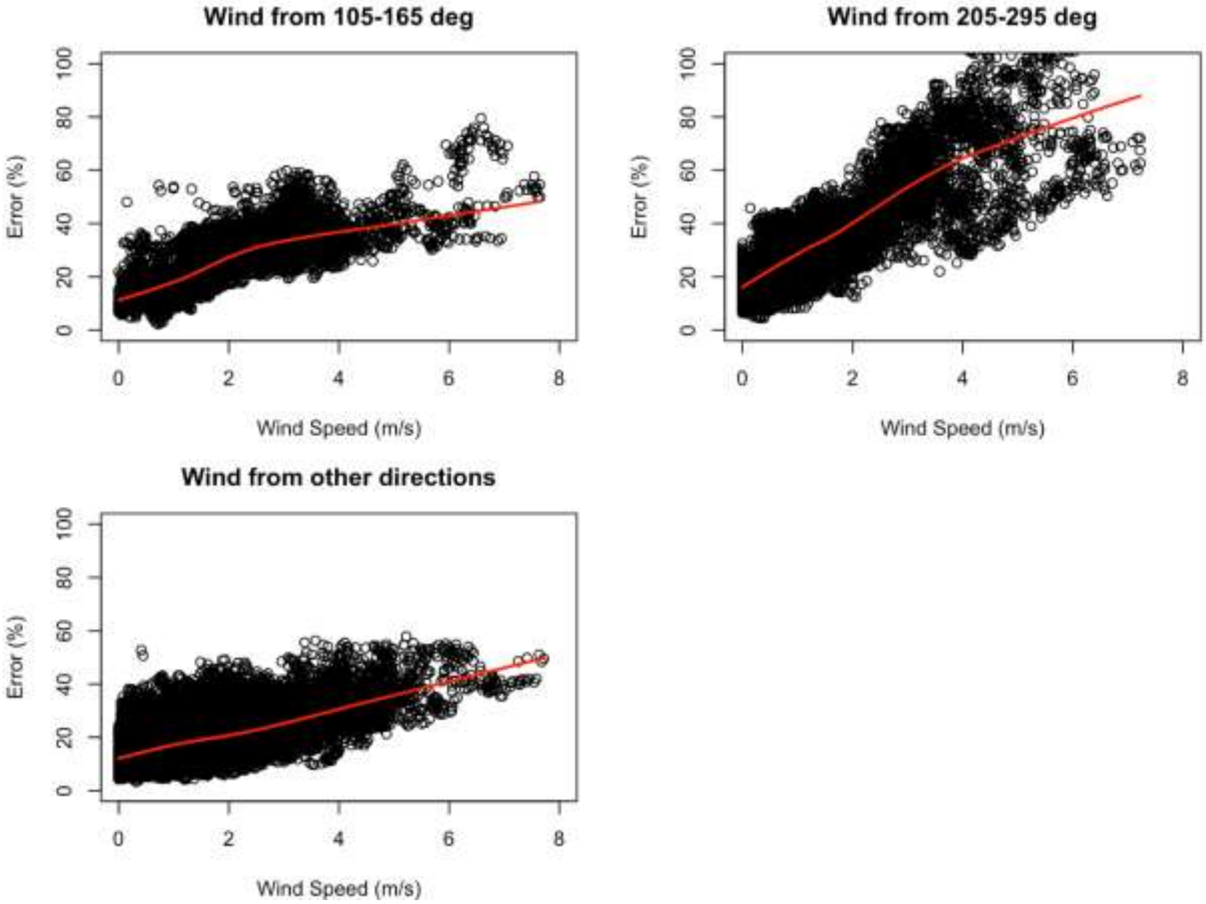


Figure 17 (continued): Effects of Wind on Measurement Error of Ebtron Gold Probe System Tested with Air Intake Hood 1



Measurement errors plotted as a function of wind directions (top), and wind speeds (bottom three panels) when wind was blowing from different directions. The red line traces the trend suggested by the data points using lowess function of R statistical software.

Source: Lawrence Berkeley National Laboratory

A linear regression was performed to account for the effect of wind speeds before determining the potential effects of air temperature and relative humidity:

$$Error\ (\%) = \ Intercept + Slope \times Wind\ Speed\ (ms^{-1})$$

The resulting intercepts and slopes, shown in Table 4, are all statistically significant at 99.9 percent confidence intervals.

Table 4: Regression Results Showing Effects of Wind Speeds on Measurement Error of Ebtron Gold Probe System Tested with Air Intake Hood 1

	Intercept (Std. Error)	Slope (Std. Error)	R^2
Wind from 105 to 165 degrees	13.10 (0.17)	6.52 (0.07)	0.60
Wind from 205 to 295 degrees	17.86 (0.26)	11.16 (0.10)	0.66
Wind from other directions	13.24 (0.11)	4.37 (0.05)	0.35

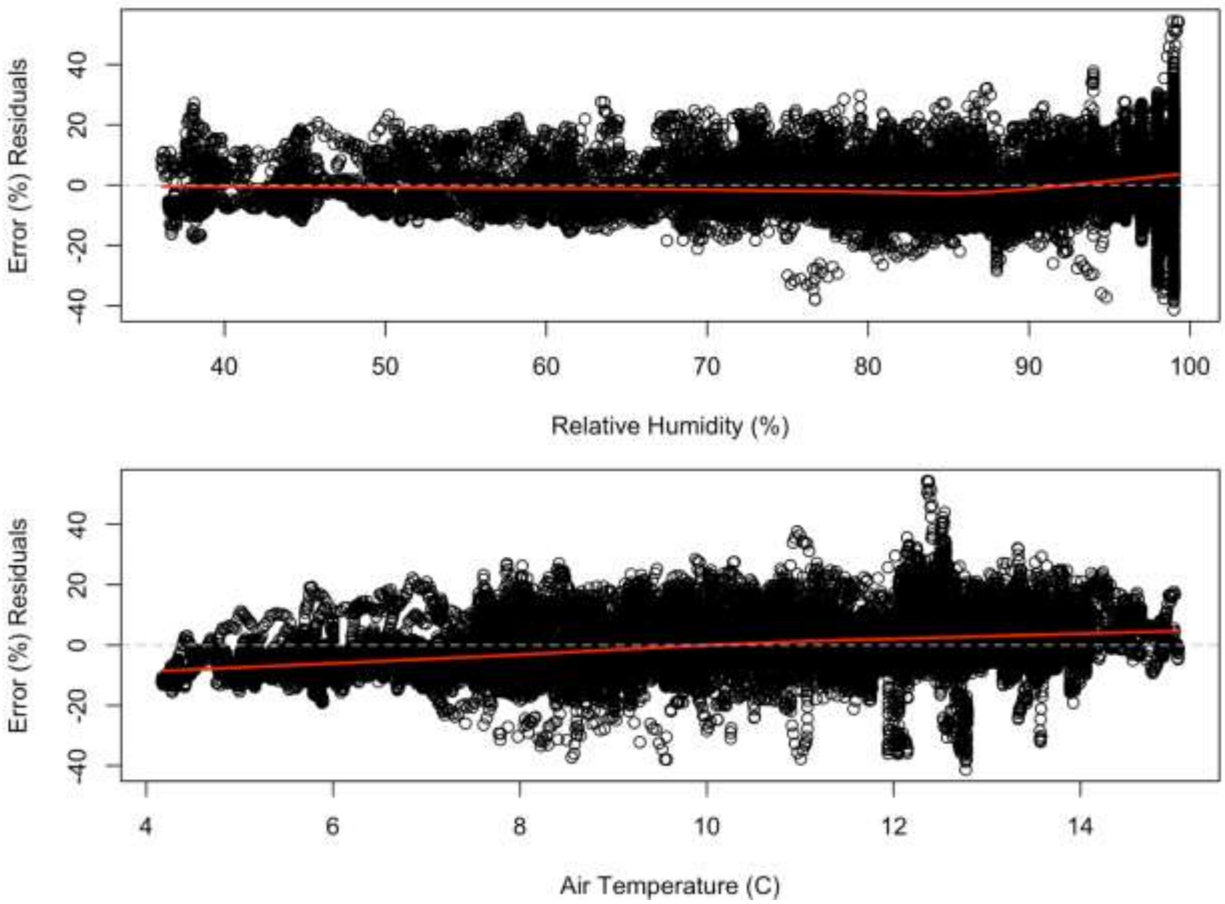
Source: Lawrence Berkeley National Laboratory

Next, modeled residuals were calculated, that is, observed measurement error minus fitted value from the regression. Modeled residuals were plotted against air temperature and relative humidity to determine the potential effects of air temperature and relative humidity on measurement errors, after accounting for effects of wind (Figure 18). Measurement errors were higher when relative humidity approached 100 percent, such as when it rained or during early morning fog. Otherwise, relative humidity did not appear to affect measurement errors of the Ebtron Gold probe system, after accounting for the effect of wind. Air temperature had a minor effect on the measurement errors of the Ebtron Gold probe system, after accounting for the effect of wind.

A similar analysis was performed for the Ebtron Gold probe system when installed with air intake hood 2. Results are shown in Appendix B. The effect of wind on measurement errors was less notable. An increase in wind speed by 5 m s^{-1} would result in a change in measurement errors in the range of 15 percent to 30 percent. Selecting an intake hood (for example, hood 2) that provides more sheltering from wind can reduce the effect of wind. However, at low wind speeds, the Ebtron Gold probe system performed better when used with air intake hood 1. Even though hood 2 appeared to reduce the wind effect, it caused airflow path to change direction between the entry plane and the location of the Ebtron Gold probe system, which likely explained the larger measurement errors observed.

EAMS results as a function of wind are shown in Appendix B. A small wind effect was observed when a vertical-blade louver was used. An increase in wind speed by 5 m s^{-1} would result in a change in measurement errors by approximately 20 percent. When the EAMS was tested with the horizontal-blade louver a larger wind effect was observed when wind was coming from between 95 and 165 degrees, where an increase in wind speed by 5 m s^{-1} would result in a change in measurement errors of 75 percent. Wind from other directions had a smaller effect on measurement errors (approximately 25 percent). Overall, the vertical-blade louver, which has more blades than the horizontal louver and that has higher maximum air velocities, appeared to be better at reducing the effect of wind on measurement errors of the EAMS. However, the vertical-blade louver would require a calibration factor so that readings would agree with the reference airflow meter.

Figure 18: Effects of Relative Humidity and Temperature on Measurement Error of Ebtron Gold Probe System Tested with Air Intake Hood 1



Modeled residual errors (after fitted to effects of wind) plotted as a function relative humidity (top) and air temperature (bottom). The red line traces the trend suggested by the data points using lowess function of R statistical software.

Source: Lawrence Berkeley National Laboratory

Discussion

The test results suggest that accuracies of OAMTs are highly affected by the louver or air intake hood design. Larger measurement errors can also occur with high wind speeds and certain wind directions, especially when wind was directed towards the outdoor air inlet. Air temperature, and humidity to a less extent, can also affected measurements of some OAMTs.

The Ebtron Gold probe system was tested with two air intake hood designs. The test results suggest that accuracies of OAMTs are highly affected by the air intake hood design. Hood 1 has the benefit of having a straight airflow path as air enters into the hood. However, it provides little protection from wind. The data indicate that an increase in wind speed by 5 m s^{-1} from some directions would result in a change in measurement errors in the range of 20 percent to 50 percent. Further, higher measurement errors were observed when the relative humidity approached 100 percent. Hood 2 has the disadvantage that it caused the airflow path to change direction from the entry plane to where the Ebtron Gold probe system was placed in the duct. At low wind speeds, higher measurement errors occurred with hood 2 compared to hood 1. However, hood 2 is more protective against wind effects. Where high wind speeds are common, hood 2 may result in more reliable measurements than hood 1. However, if measurements during periods of high wind speed are discarded, better accuracy can be obtained with hood 1.

The strengths of this study include the use of highly accurate reference flow meters, the testing with two different air intake louvers and two different air intake hoods, and the test system location which allowed environmental conditions to vary naturally. One limitation is that the tests used only one of each model of OAMT and occurred over a limited period of time (two weeks). Also, the air intake dimensions were limited to 0.61 m by 0.61 m. Large HVAC systems with louvers often have a larger air intake system in which the overall airflow is less affected by the edges of the air intake system. Thus, it is possible that measurement accuracy is better in larger systems than in the tests reported in this report. But the challenge of measuring low air velocities remains for larger systems because of the need to limit moisture entry into louvers or air intake hoods. Non-uniform air velocity profile is another problem that will also affect larger systems.

Conclusions

It is important for manufacturers of OAMTs to provide information on measurement accuracies that are specific to the louver or air intake hood used. Alternately, building operators may be able to obtain calibration factors for specific OAMT installations from air balance companies; however, the accuracy of such calibrations is unknown. Use of current technologies, as represented by the two OAMTs tested in this study and the commercially available OAMTs evaluated in prior research, will likely result in high measurement errors if used to measure airflow at minimum OA in HVAC systems with economizers.

Based on this work and prior evaluations of OAMTs, to improve measurement accuracy of OAMTs one can condition the airflow so that the air speed is as uniform as possible and the airflow direction is parallel to the duct perimeter at the location of OAMT's sensors. While OAMTs could be designed to sufficiently condition the airflow at the location of sensors, field-based conditioning of the airflow (for example via use of long straight ducts for incoming OA) may often be impractical. Also, OAMTs must use velocity sensors that can accurately measure the low airspeeds encountered in outdoor air intakes when minimum rates of outdoor airflow are provided in HVAC systems with economizers. By providing separate OA intake paths and dampers for minimum OA and economizer air, the required velocities can be maintained at the sensors of OAMTs; however, HVAC costs are increased, and this also introduces additional complexity to control sequences.

Long-Term Assessment of Carbon Dioxide Sensors Marketed for Use in Demand-controlled Ventilation Systems

Objectives

This research task evaluated the accuracy of current-generation CO_2 sensors intended for DCV applications. The long-term accuracy of CO_2 sensors is critical for DCV systems to function properly so that adequate ventilation and the intended energy savings can be achieved. Factors that may contribute to drift in sensor calibration include changes in the amount of IR light emitted by the IR source, changes in detector sensitivity, and changes the IR reflectivity of cell walls. Variable environmental conditions (for example air pressure) can also potentially affect calibrations.

Methods

Three each of seven different CO_2 sensor models were installed for two years (March 2015 to March 2017) in three study spaces that had different CO_2 time-varying concentrations: a classroom, a general office space, and a conference room. The accuracies of the CO_2 sensors were determined based on the difference between their outputs and the true CO_2 measurement from a co-located, research-grade reference CO_2 gas analyzer. The reference gas analyzer (EGM4, PP Systems, Amesbury, Massachusetts) was calibrated monthly using gas standards to check its accuracy.

Figure 19 shows the placement of CO_2 sensors and the reference instrument so they are exposed to the same CO_2 concentrations. Not shown are the power supply, data acquisition system, and temperature and humidity data logger (Onset HOBO U12, manufacturer rated accuracy: ±0.05^{o}C and ±3.5 percent RH). CO_2 sensors were mounted on a wire-framed cage, enabling air to flow freely through the array of sensors.

Table 5 identifies the seven CO_2 sensors selected for evaluation. The selection was approved by the Energy Commission contract manager during the project kickoff meeting. Representatives of a leading HVAC design and control firm and a leading HVAC manufacturer also provided input. The selected sensors span a range of designs from sensor manufacturers with a large market share. All are non-dispersive IR sensors that determine the CO_2 concentration based on the amount of adsorption of an IR light beam. Thus, each sensor contains a cell with a source of IR light and an IR detector that measures the amount of incident IR light. The fraction of IR light with a wavelength of ~4.26 μm leaving the source that reaches the detector decreases as the CO_2 concentration increases due to adsorption of the IR light by CO_2. Reflections of the IR light off of cell walls increase the effective path length between the IR source and IR detector. All seven sensors are designed to measure in the 0 to 2000 ppm concentration range. All rely on diffusion through a membrane to maintain the same concentration of CO_2 inside the cell as in the surrounding environment.

Figure 19: CO_2 Sensor Package for Evaluation Study

Source: Lawrence Berkeley National Laboratory

Three of the sensors tested (BAPI Stat 4, Telaire 8100, Airtest TR9294) employ a single wavelength of IR light. For these sensors, an automated background calibration (ABC) is used to help maintain sensor accuracy; though ABC is sometimes used in other sensor types as well. The ABC feature keeps track of the smallest amount of IR light adsorption over a period of days to weeks and automatically adjusts the sensor's calibration, under the assumption that the lowest encountered CO_2 concentration is approximately 400 ppm. This assumption is reasonable in buildings that are have regular periods without occupancy (for example, office buildings).

The AirTest TR9294 uses a long-path IR design[10] to increase signal relative to noise. It uses a "gold plated optical sensor" to improve long-term stability.

The BAPI Stat 4 24/7 and Telaire T8200 are described as "dual channel" in product literature. They employ two IR wavelengths, one wavelength at which CO_2 adsorbs the IR radiation and a reference wavelength without adsorption of IR radiation by CO_2. The sensors use the data at the reference wavelength to periodically self-calibrate. They do not have ABC. CO_2 sensors that do not rely on ABC are recommended for buildings that may be occupied at all times such that CO_2 concentrations indoors never fall to the outdoor background value (for example, call centers and hospitals).

10 AirTest TR9294 (http://www.airtesttechnologies.com/support/reference/lengthmatters.pdf).

Table 5: Selected Carbon Dioxide Sensors for Evaluation Study

ID	Make/ Model	Sensor Type	Reported Accuracy
GMW86	Vaisala GMW86	• Single beam, dual wavelength • Switchable electrical filter • "Microglow" IR source	±30 ppm or ±3% of reading 5-year stability: ±15 ppm or ±2% of reading
TR9294	AirTest TR9294	• Single beam, single wavelength • Long-path IR • Automated background calibration (ABC)	±1% of full-span or ±3% of reading
ACD05	BAPI Stat 4	• Single beam, single wavelength • ABC	±30 ppm or ±3% of reading (400–1250 ppm) ±5% of reading + 30 ppm (1250–2000 ppm)
DCD05	BAPI Stat 4 24/7	• Single beam, dual wavelength	±75 ppm
T8100	Telaire 8100	• Single beam, single wavelength, ABC	±30 ppm or ±3% of reading 15-year stability: <2% of full-scale
T8200	Telaire 8200	• Single beam, dual wavelength	±30 ppm or ±3% reading 10-year stability: <5% of full-scale or <10% of reading
COZIR	Gas Sensing Solutions	• Single beam, single wavelength • LED IR source • ABC	±50 ppm or ±3% of reading Non-linearity <1% of full-scale

Source: Lawrence Berkeley National Laboratory

The Vaisala GMW86 uses just one IR filter and detector. The micromechanical filter[11] can electrically switch between a state that adsorbs and does not adsorb the IR light. This feature is employed to make a reference measurement internally and maintain the

[11] Vaisala GMW86 (http://www.vaisala.com/Vaisala%20Documents/Technology%20Descriptions/CEN-G-CARBOCAP-Technology-description-B210780EN.pdf).

sensor calibration. Vaisala GMW86 also uses a MEMS IR source[12] that the manufacturer claimed will help to ensure long-term stability over time.

The COZIR uses a light emitting diode (LED) as the IR source. The LED source consumes less energy and has a faster warm-up time than the other IR sources, making it possible to power the COZIR using batteries for wireless applications. For this evaluation study, however, COZIR was continuously powered, same as the other CO_2 sensors. The COZIR also uses ABC.

The CO_2 sensors provided analog current outputs (4–20 mA) that were converted to a voltage using high precision low-temperature-coefficient resisters. The voltages were logged with an Arduino micro-controller with a 12-bit analog to digital converter. Voltages were recorded at a one-minute time interval throughout the two-year evaluation study period.

Reference Carbon Dioxide Instrument

The reference CO_2 instrument, EGM4 (PP Systems, Amesbury, MA) has a rated accuracy of better than 1 percent of the full-scale concentration (0-5,000 ppm measurement ranges). The instrument automatically compensates for changes in temperature and pressure. It also performs automatic zero-check periodically to adjust the baseline response by passing the sample air stream through a soda-lime cell that removes all CO_2. The researchers' prior experience with these instruments found their calibration to be stable. The manufacturer recommended replacing the soda lime when two-thirds were exhausted, as indicated by a change in color from blue to brown. Researchers checked the soda-lime cell monthly, and replaced the soda lime once every two months. The rate of replacement was more frequent than the manufacturer's recommendation. The team observed only a small portion (less than 10 percent) of soda lime that had changed color in a given replacement.

The accuracy of the reference instrument was checked at the study sites using calibration bags (Figure 20) prepared using a primary standard CO_2 standard gas and a gas divider that precisely mixes the calibration gas with CO_2-free zero air (20.9 percent oxygen balance nitrogen). During the first four months of deployment, the research team checked accuracy of the reference instrument every two weeks at five CO_2 concentrations: 0, 493, 986, 1,480, 1,726, and 2,466 ppm. After that, accuracy was checked monthly. See Appendix C for results from each accuracy check.

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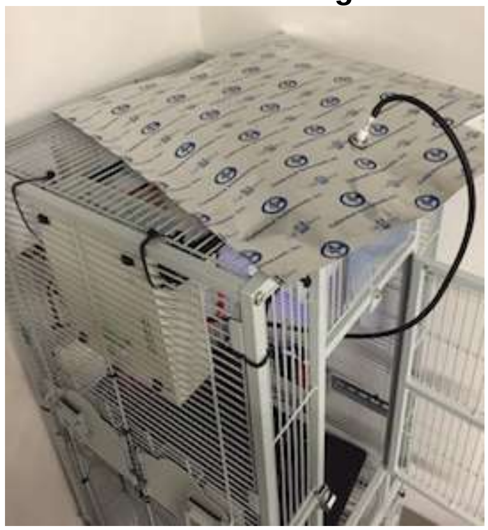
12 Vaisala GMW86 (http://www.vaisala.com/en/industrialmeasurements/knowledgebase/technologydescriptions/Pages/Microglow.aspx).

Figure 20: Carbon Dioxide Reference Instrument Accuracy Check using Calibration Bags



Source: Lawrence Berkeley National Laboratory

Test Locations

One sensor package was installed at a non-obtrusive location with access to a power outlet in each of three different types of indoor environments. For this task, it was not important to assure that the measured CO_2 concentrations were spatially representative of the room.

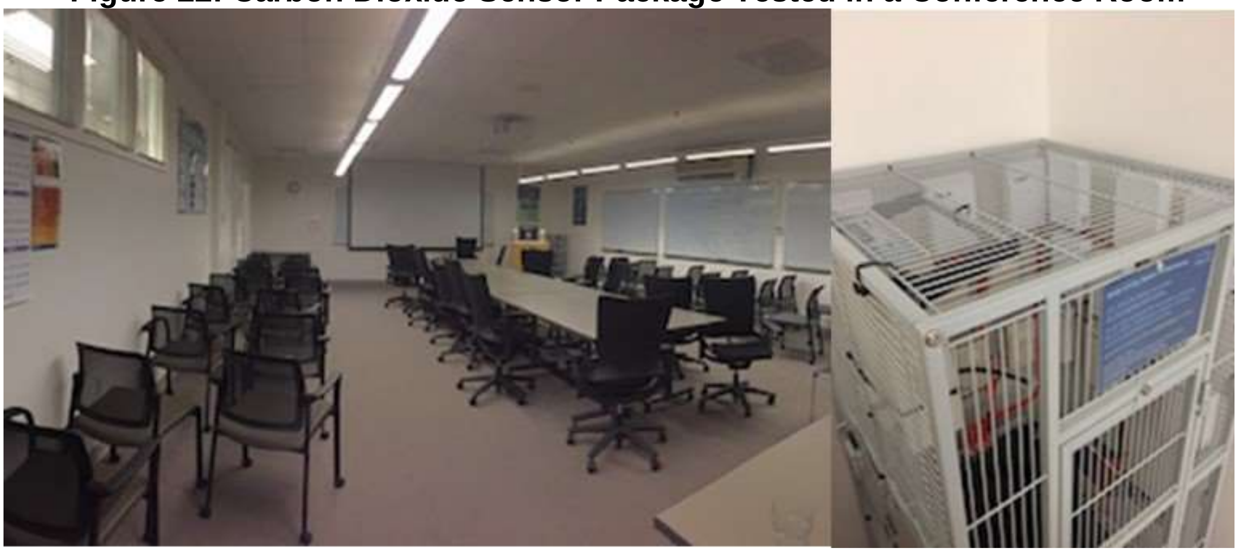
One location was an open plan general office space (Figure 21). Concentrations of CO_2 in offices in California are usually maintained below 1,000 ppm. The office space studied is an LBNL building, where the daily peak CO_2 concentrations were typically between 600 and 700 ppm.

Figure 21: Carbon Dioxide Sensor Package Tested in a General Office Space

Source: Lawrence Berkeley National Laboratory

The second location was a conference room (Figure 22). Based on prior studies, CO_2 concentrations in conference rooms are highly variable with peak concentrations often exceeding 1,000 ppm and sometimes becoming as high as 2,000 ppm. The 60 m^2 (820 ft^2) conference room had 40 seats, and was used daily for meetings and seminars. CO_2 concentrations reached 1,000-1,500 ppm when the conference room was occupied.

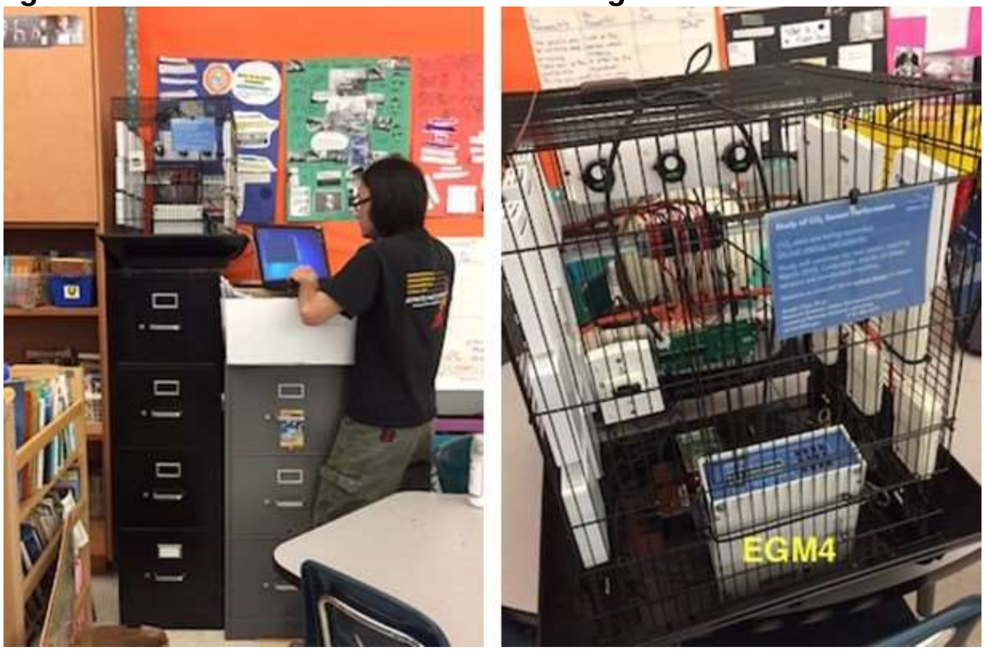
Figure 22: Carbon Dioxide Sensor Package Tested in a Conference Room



Source: Lawrence Berkeley National Laboratory

The third location was an elementary school classroom (Figure 23). Prior studies indicated that many classrooms have CO_2 concentrations that routinely exceed 1,000 ppm, with some classrooms having peak concentrations of 2,000 to 4,000 ppm. Peak CO_2 concentrations exceeding 2,000 ppm occurred routinely in the studied classroom.

Figure 23: Carbon Dioxide Sensor Package Tested in a Classroom



Source: Lawrence Berkeley National Laboratory

Previous studies found that in some classrooms, concentrations of CO_2 do not fall below 1,000 ppm each night. Table 6 shows the summary statistics of CO_2 concentrations measured between 2 a.m. and 5 a.m. and on weekends (Saturday and Sunday) in the three studied spaces.

Table 6: Carbon Dioxide Concentrations Measured in Three Study Spaces When Unoccupied

	Mean	Median	5th Percentile	95th Percentile
Office	409 ppm	407 ppm	392 ppm	430 ppm
Conference Room	409 ppm	408 ppm	393 ppm	428 ppm
Classroom	427 ppm	423 ppm	403 ppm	466 ppm

Unoccupied hours are defined as nightly between 2 and 5 am, and on weekend (Sat-Sun).

Source: Lawrence Berkeley National Laboratory

The office and conference room locations had low CO_2 concentrations of roughly 410 ppm. The low CO_2 concentrations in the classroom were at 420 ppm. The classroom had a slightly elevated CO_2 background may be explained by its location near a busy retail area. The office and conference room are in LBNL buildings, which is located a short distance away from downtown Berkeley, California.

Data Analysis

The researchers computed measurement error of the CO_2 sensors at two ranges of concentrations: 700 ppm (between 650 and 750 ppm) and 1,000 ppm (between 950 and 1,050 ppm).

Measurement error and absolute value error are calculated as follows:

$$Error\ (ppm) = CO2_{Sensor} - CO2_{Ref}$$

$$Absolute\ value\ error\ (ppm) = abs(Error)$$

Measurement errors at 700 ppm and 1,000 ppm were selected because they span the relevant range of set point concentrations for DCV in commercial buildings. The absolute value error of CO_2 sensors at these concentrations was calculated and compared with Title 24 requirement of ±75 ppm.

Linear regression was employed to obtain the slope and zero offset, and the regression results were applied to predict measurement error of CO_2 sensors.

$$CO2_{Sensor} = Slope * CO2_{Ref} + Zero\ Offset$$

The "gain error" was defined as the difference in concentration at a given concentration (e.g., x = 1,000 ppm), minus the zero offset error. A "gain" of zero would mean that a CO_2 sensor has the same error (ppm) that equals the zero offset regardless of concentrations.

Analysis based on regression results has the advantage that it makes use of all the data points collected from the two-year monitoring period. In contrast, calculation of measurement errors at 700 ppm and 1,000 ppm only used a small fraction of the data collected, when CO_2 concentrations were within the specified ranges. Note that in the studied office space, CO_2 concentrations never exceeded 1,000 ppm.

Table 7: Number of Hours when Measured Carbon Dioxide at Different Concentration Ranges

CO_2 Concentrations	Office (hours)	Conference Room (hours)	Classroom (hours)
650–750 ppm (~700 ppm)	443	160	235
950–1,050 ppm (~1,000 ppm)	Not Reached	16	163
500–2000 ppm	3401	1263	2060

Source: Lawrence Berkeley National Laboratory

All analyses used CO_2 concentrations measured only during occupied hours, that is, weekdays from 8 a.m. to 6 p.m. for the office and conference room, and 8 a.m. to 2 p.m. for the classroom. Data on public holidays were excluded. Data collected during summer breaks and other school holidays were excluded for the classroom. Five-minute running averages were computed from the minute-by-minute concentrations measured by the reference instrument and CO_2 sensors, before comparing the two sets of concentration data. This averaging step was intended to reduce the effects of data noise. For the linear regression analysis, researchers only considered concentrations in the range of 500 and 2,000 ppm as measured by the reference instrument.

Results

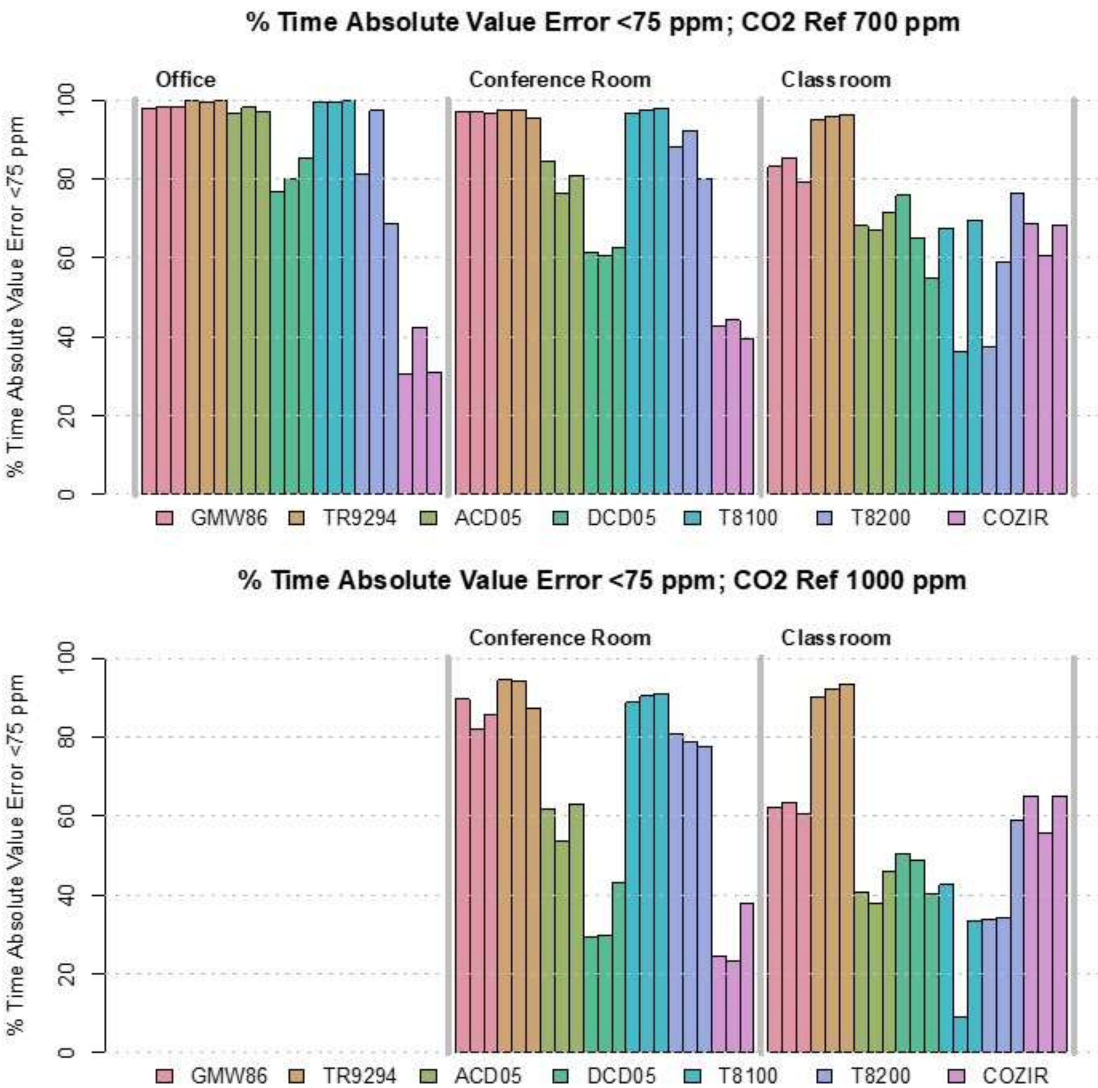
Detailed statistics of the CO_2 sensor measurement errors, absolute value of errors, fitted slope and intercept, and estimated offset and gain are tabulated in Appendix C. For an unknown reason, one of the T8200 sensors (second replicate) in the office space put out data sporadically during some parts of the study period. This sensor's data were excluded from the analysis if too few data were available for trending analysis. Since this CO_2 sensor outputted reasonable values for at least half of the time during the two-year study period, many of the analyses were able to consider the entire dataset.

Figure 24 shows the percentage of time when the absolute value error of CO_2 sensors was less than 75 ppm. In the office, the GMW86, TR9294, ACD05, and T8100 sensors performed very well, where the absolute value error was less than 75 ppm more than 95 percent of the time. DCD05 and T8200, which are "dual channel" CO_2 sensors, showed somewhat lower accuracy, with absolute value error exceeding 75 ppm about 20 percent of the time.

The COZIR did not agree with the reference CO_2 measurements in any of the study spaces. Unlike other CO_2 sensors marketed for DCV, COZIR has software that allows users to specify operating parameters. It is possible that COZIR would agree better with the reference instrument by adjusting some of the factory-default parameters (e.g. assumed background concentration = 400 ppm, calibration frequency once every 8 days). For this evaluation study, all adjustable parameters were maintained at factory defaults, because the knowledge required to make appropriate adjustments is likely not available to the majority of users.

Figure 24 shows that agreement between CO_2 sensors and the reference instrument can differ in different study spaces. While some CO_2 sensors performed similarly in all three spaces (e.g., AirTest TR9294), other sensors showed larger differences. Among those sensors that performed differently in different study spaces, the closest agreements with respect to the reference instrument tended to occur in the office, where CO_2 concentrations varied the most gradually over a day with daily peak CO_2 concentrations typically between 600 and 700 ppm. Some CO_2 sensors showed more differences with respect to the reference instrument in the classroom only (e.g., Telaire T8100 and T8200, Vaisala GMW86), while others showed more differences in conference room also (BAPI Stat 4 and Stat 4 24/7).

Figure 24: Percentage of Time When Carbon Dioxide Sensor Absolute Value Error Less Than 75 parts per million



The upper plot shows results evaluated at CO_2 reference concentration at ~700 ppm (between 650 and 750 ppm). The lower plot shows results for CO_2 reference concentration at ~1,000 ppm (between 950 and 1,050 ppm). In the lower plot, results for the office were not available because CO_2 concentrations did not reach 1,000 ppm in that space.

Source: Lawrence Berkeley National Laboratory

Table 9 through Table 11 summarize the mean error and mean absolute value error of the CO_2 sensors.

Table 8: Mean Error Summary (CO2 Reference 700 parts per million)

	Office	Conference Room	Classroom
GMW86	-25	-32	-29
TR9294	-10	-24	-9
ACD05	-23	-29	-48
DCD05	-19	-64	-46
T8100	-9	-12	71
T8200	-41	-25	-63
COZIR	91	80	44

Source: Lawrence Berkeley National Laboratory

Table 9: Mean Error Summary (CO2 Reference 1,000 parts per million)

Conference Room	Classroom
GMW86	-35
TR9294	-13
ACD05	-35
DCD05	-98
T8100	-7
T8200	-4
COZIR	105

Source: Lawrence Berkeley National Laboratory

Table 10: Mean Absolute Value Error (CO_2 Reference = 700 ppm)

	Office	Conference Room	Classroom
GMW86	26 (4%)	33 (5%)	44 (6%)
TR9294	14 (2%)	28 (4%)	25 (4%)
ACD05	26 (4%)	52 (7%)	62 (9%)
DCD05	55 (8%)	71 (10%)	65 (9%)
T8100	14 (2%)	24 (3%)	76 (11%)
T8200	45 (6%)	41 (6%)	72 (10%)
COZIR	91 (13%)	86 (12%)	62 (9%)
Mean	39 (6%)	48 (7%)	58 (8%)

Percent of reference concentration.

Source: Lawrence Berkeley National Laboratory

Table 11: Mean Absolute Value Error (CO_2 Reference = 1,000 ppm)

Conference Room	Classroom
GMW86	43 (4%)
TR9294	32 (3%)
ACD05	79 (8%)
DCD05	107 (11%)
T8100	35 (3%)
T8200	49 (5%)
COZIR	111 (11%)
Mean	65 (6%)

Percent of reference concentration.

Source: Lawrence Berkeley National Laboratory

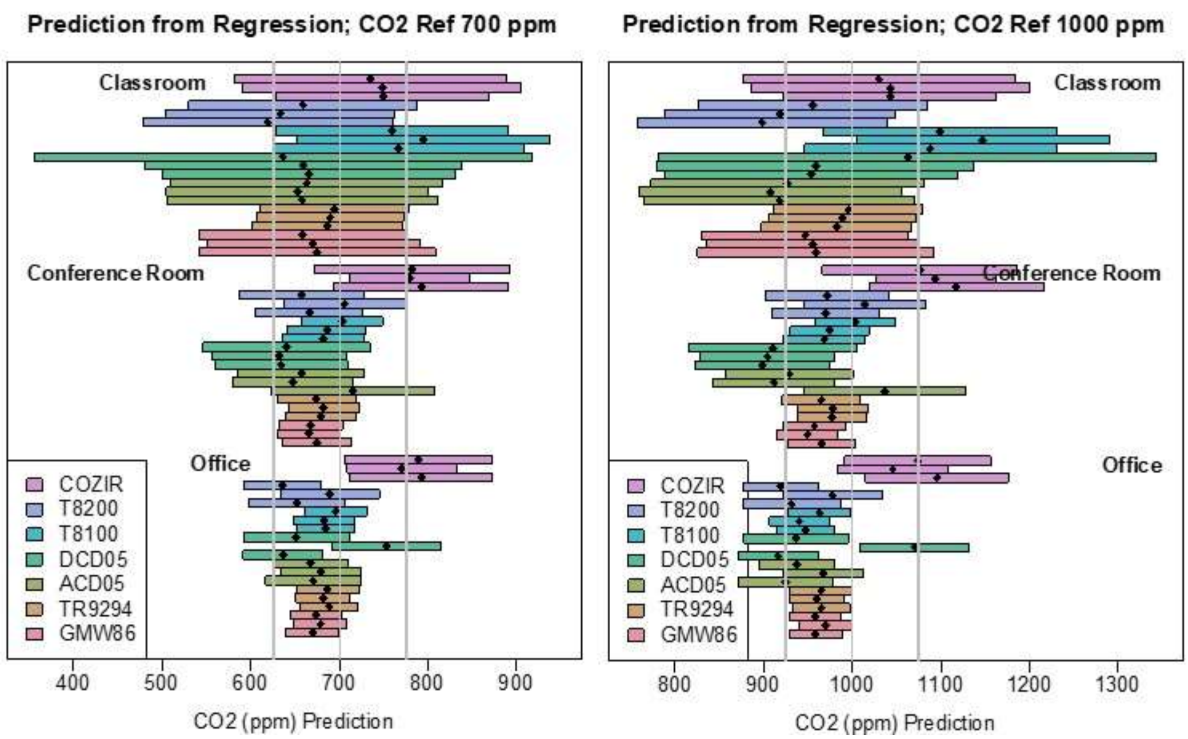
With the exception of COZIR, the research team found that CO_2 sensors tended to slightly underestimate true CO_2 concentrations. The averages of absolute values of error of CO_2 sensors differed by manufacturer and sensor type. The overall average of mean absolute values of error of seven CO_2 sensors was 7 percent from this study (ranged between 6 percent in the office, and 8 percent in the classroom).

Fisk, Faulkner et al. (2009) evaluated accuracy of 208 CO_2 sensors located in 34 commercial buildings. Field calibration checks of 90 sensors—in which sensor accuracy was checked at multiple CO_2 concentrations using a primary standard calibration gas—also found small negative average errors: -26 ppm and -9 ppm at 760 ppm and 1,010 ppm, respectively. For CO_2 sensors that use ABC (TR9294, ACD05, and T8100), the small negative errors might be explained by CO_2 background concentrations slightly above the assumed value of 400 ppm. However, small negative errors were also found among CO_2 sensors that do not use ABC (GMW86, DCD05, and T8200). From their prior study, Fisk, Faulkner et al. (2009) calculated the averages of absolute values of error were 118 ppm (16 percent) and 138 ppm (14 percent) at concentrations of 760 ppm and 1,010 ppm, respectively. In comparison, this study found lower absolute values of error among the CO_2 sensors selected (less than 10 percent typically).

Results from the linear regression fit are shown in Appendix C. The slope and intercept were used to predict outputs from the CO_2 sensors at reference concentration of 700 and 1,000 ppm.

Figure 25 shows the central estimates and 95 percent prediction intervals. Results from the linear regression were also used to predict the percentage time when errors greater than ±75 ppm are expected. The predicted percentages of time for the individual CO2 sensors are similar to the values shown in Figure 24.

Figure 25: Predictions of Carbon Dioxide Sensor Concentrations



Black dots show the central estimates; widths of colored bars show 95% prediction intervals.

Source: Lawrence Berkeley National Laboratory

Fisk, Faulkner et al. (2009) found that at 760 ppm, 47 percent of sensors had errors greater than ±75 ppm, and 37 percent of sensors had errors greater than ±100 ppm. At 1010 ppm, 40 percent of sensors had errors greater than ±75 ppm, and 31 percent of sensors had errors greater than ±100 ppm. As a group, the seven CO_2 sensors evaluated in this study had a better accuracy in the office and conference room setting, compared to the prior results by Fisk, Faulkner et al. (2009). In the office, 15 percent (at 700 ppm) and 24 percent (at 1,000 ppm) of the 21 CO_2 sensors (3 replicates each of 7 models) were predicted to have errors greater than ±75 ppm. In the conference room, 19 percent (at 700 ppm) and 28 percent (at 1,000 ppm) of the sensors were predicted to have errors greater than ±75 ppm. However, in a more challenging environment such as the classroom, the accuracy in the present study and the prior study were similar: 38 percent (at 700 ppm) and 44 percent (at 1,000 ppm) of sensors would have errors greater than ±75 ppm. Note that the prior study included a wide range of building types: healthcare, education, software industry, judicial, library, utility, corrections, law enforcement, museum, entertainment, retail, and state/federal/private offices.

Figure 26 compares the zero offset of CO_2 sensors with respect to the reference instrument, and the additional error at 1,000 ppm ("gain") caused by a change in the response slope of CO_2 sensor. Note that the very large zero offset and gain estimated for DCD05 (replicate 2) is due to the nonlinear relationship between sensor output and reference CO_2 concentration (see Appendix C for scatter plot of this sensor). The other two replicates of DCD05 did not show this nonlinearity.

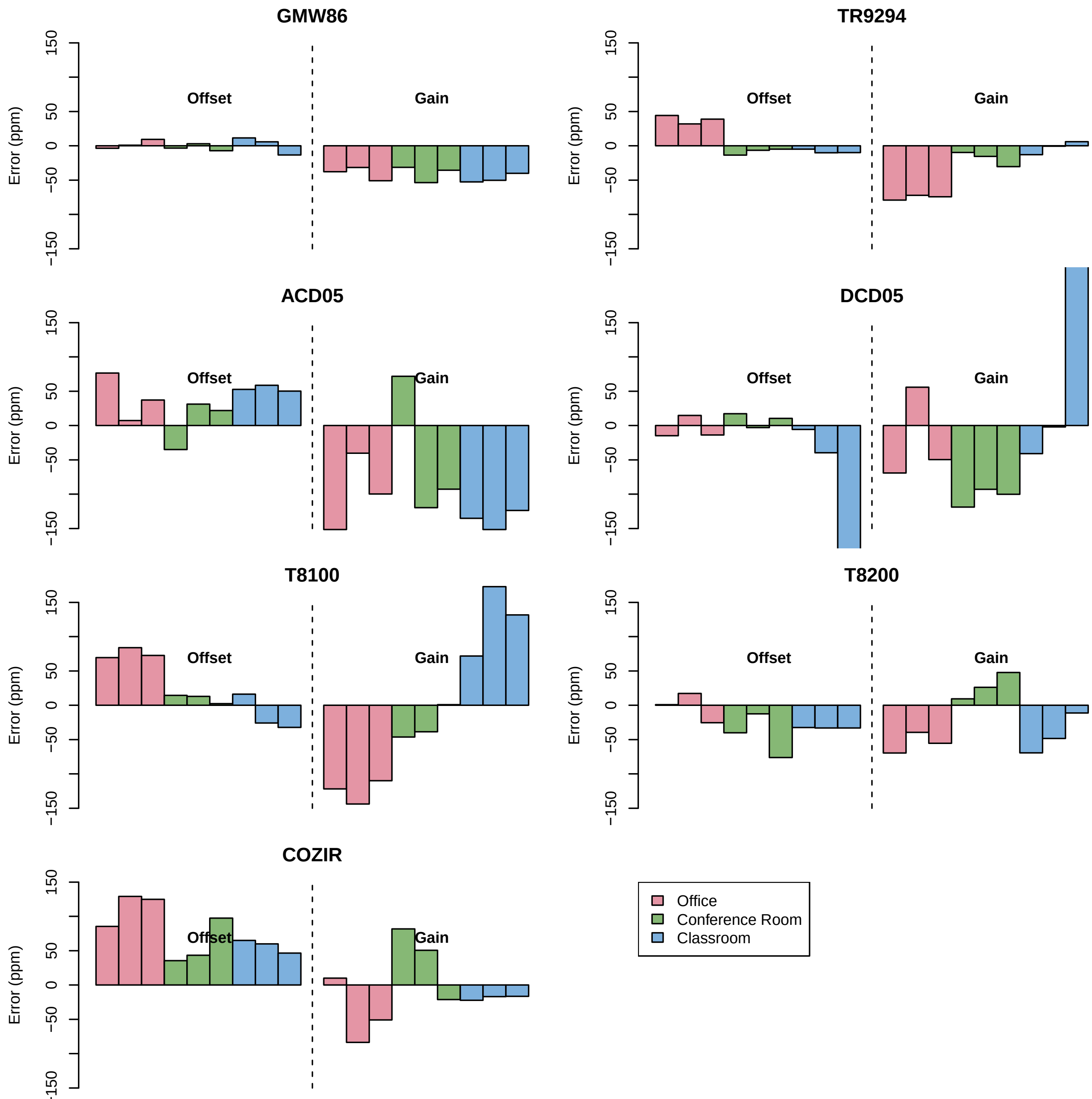
Measurement errors of the COZIR are dominated by offset, whereas larger fraction of errors of ACD05 and T8100 (single wavelength with ABC) are because of gains in sensor response. ABC is intended to maintain stability of the CO_2 sensor at 400 ppm, so it is not surprising to observe smaller offset error compare to gain from the analysis of ACD05 and T8100. On the other hand, CO_2 sensors that do not rely on ABC (e.g., DCD05 and T8200) are more equally affected by both zero offset and gain errors.

GMW86 and TR9294 are the two CO_2 sensors that showed higher accuracy than others in the evaluation. Manufacturers of these two sensors use different approaches to avoid drift and maintain long-term stability. Figure 26 shows that these two CO_2 sensors tend to have a negligible zero offset and small gain errors, compared to the other CO_2 sensors evaluated in this study.

The linear regression method was also employed to estimate concentrations measured by CO_2 sensors at different periods during the two-year evaluation study, when the reference instrument reads 1,000 ppm. Figure 27 shows that only a few of the CO_2 sensors: GMW86, T8100, and T8200, showed a systematic change over time. GMW86 sensors showed an increase in underreporting of CO_2 concentrations with time in classroom only. T8100 and T8200 showed systemic changes in at least one CO_2 sensor tested in all three spaces. T8100 showed a slight increase in sensed CO_2

concentrations, whereas T8200 showed a slight decrease in sensed CO_2 concentrations with time.

Figure 26 Estimated Zero Offsets and Gain Errors of Carbon Dioxide Sensors

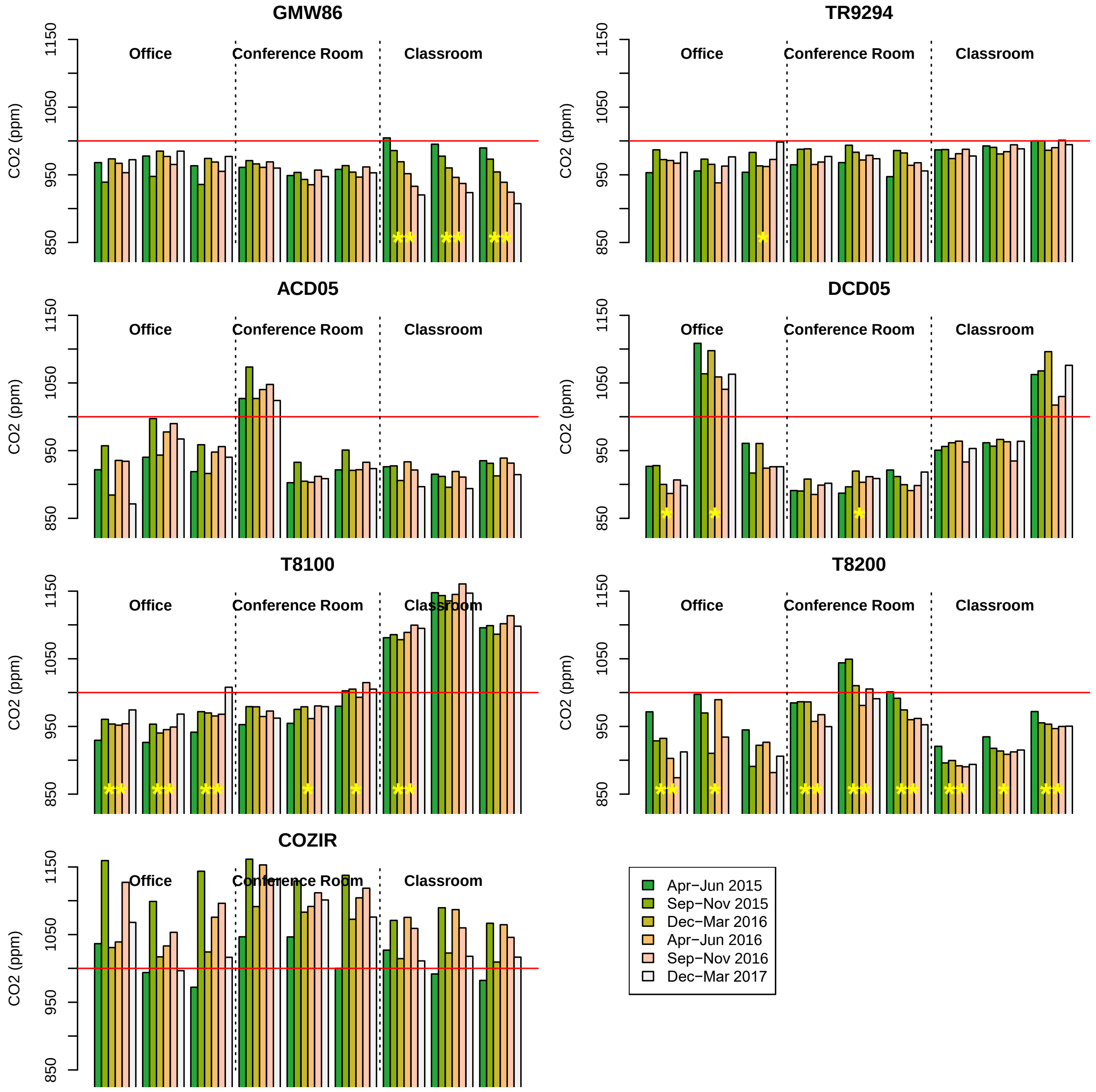


Zero offsets are determined from the intercept term of linear regression between CO_2 concentrations measured by CO_2 sensors with respect to the reference concentration. Gain errors in response of CO_2 sensors are shown at a reference concentration of 1,000 ppm.

Source: Lawrence Berkeley National Laboratory

Another method was also used to estimate the change in CO_2 sensor response as a function of time. The percent change in CO_2 sensor output from one year to the next were calculated, at a reference concentration of 1,000 ppm, by comparing the three paired periods shown in Figure 27: (1) Apr-Jun 2015 and Apr-Jun 2016, (2) Sep-Nov 2015 to Sep-Nov 2016, and (3) Dec-Mar 2016 to Dec-Mar 2017. Appendix C shows resulted zero offsets and gains from linear regression performed using data from these six periods.

Figure 27: Changes in Carbon Dioxide Sensor Output during Two-Year Evaluation Period

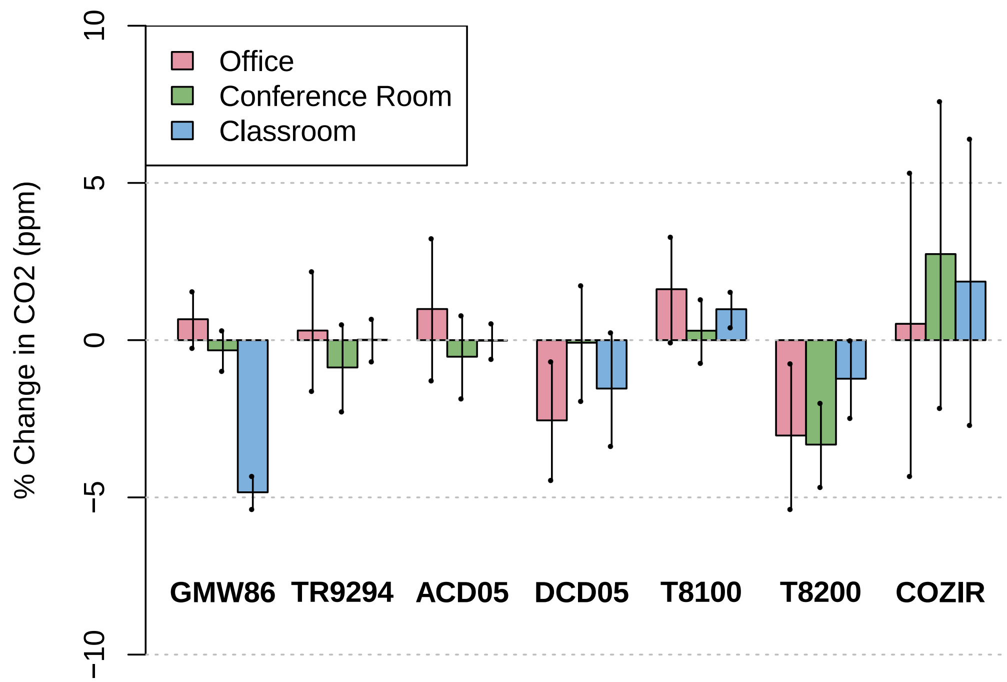


Predictions of CO_2 concentrations using regression fits from different periods. Yellow asterisks (* and **) indicate that the change in predictions with time are statistically significant at 90 percent and 80 percent confidence limits, respectively, assuming that the change in predictions is linear with time.

Source: Lawrence Berkeley National Laboratory

Figure 28 shows the mean percent change in one year by comparing three paired times of three replicates of CO_2 sensors. Results from this analysis are consistent with the trends shown in Figure 27. GMW86 shows a 5 percent decrease in CO_2 response from one year to the next in the classroom, but negligible change in response for office and conference room. CO_2 sensors that have ABC feature either showed negligible change in response (TR9294 and ACD05), or small positive changes in response (T8100 and COZIR). On the other hand, CO_2 sensors that do not have ABC showed a negative change in response (DCD05 and T8200, and also GMW86 when evaluated in classroom).

Figure 28: Mean Percent Change in Carbon Dioxide Sensor Output Over One Year



Bars showing mean percent change calculated from three paired periods that are one year apart and from three replicates of CO_2 sensors. Overlaying lines show ± standard deviation.

Source: Lawrence Berkeley National Laboratory

Discussion

CO_2 sensors are more likely to measure concentrations within the ±75 ppm requirement per Title 24 in the office, compared to the other two study spaces. This shows that accuracy of CO_2 sensors is a function of the concentration time profile of the space. CO_2 concentrations increased and decreased more gradually in the office, and peak concentrations were smaller in the office. In comparison, changes in CO_2 concentrations in the conference room and classroom tended to be more abrupt due to intermittent occupancy pattern (e.g., meeting attendants entering the conference room at the same time, students entering the classroom at the same time). The analysis used a 5-minute averaging time in all comparison between CO_2 sensor response and concentrations measured by the reference instrument. Better agreement between CO_2 sensor and reference instrument may result if a longer averaging time (e.g., 15 minutes) is used.

Similar to findings reported by Fisk, Faulkner et al. (2009), this study found mostly negative errors with respect to the reference CO_2 concentration. Negative errors may possibly be explained in CO_2 sensors that use ABC where the assumed 400 ppm background is actually too low for the space where the sensor is installed[13]. However, even CO_2 sensors that do not use ABC, tended to underestimate CO_2 concentrations. Another possible reason is that air pressure in the study space differed from the assumed sea level value. NBCIP (2010) found a positive relationship between barometric pressure and CO_2 sensor response. LBNL buildings (office and conference room study spaces) are located approximately 300 m above sea level, but the classroom is near sea level (60 m elevation). Sensor response was not adjusted for elevation above sea level because most users of CO_2 sensors at locations with such moderate elevations make no adjustments. Of the seven CO_2 sensors types evaluated in this study, only two of them (Telaire T8100 and T8200) provided pressure dependence information in their product literature that would allow users to make such an adjustment (increase CO_2 reading by 0.135 percent per mm Hg, or 1 percent per kPa). NBCIP (2010) found pressure dependence to range between 7.6 percent and 10.7 percent per psi (mean = 8.9 percent per psi, or 1.3 percent per kPa) among the 15 sensors evaluated for accuracy. Over the two-year study period, the average barometric pressure measured at LBNL onsite meteorological tower was 14.3 psi (98.6 kPa). The 0.4 psi (2.7 kPa) difference with respect to the average barometric pressure at sea level (14.7 psi, 101.3 kPa) means that at a reference concentration of 1,000 ppm, an average of -36 ppm difference is expected from CO_2 sensors output with respect to the reference measurement. The classroom is located near sea level. Data from a nearby weather station confirmed that the average barometric pressure was 14.7 psi (101.3 kPa). At both locations, the standard deviation of barometric pressure was 0.07 psi. Thus, the variability in barometric pressure is expected to result in a difference in CO_2 concentration within ±12 ppm for 95 percent of the time.

One strength of this study is that by tracking the accuracy of CO_2 sensors over two years in three occupied spaces, potential changes in sensor response over time were assessed. CO_2 sensors with ABC tended to be more stable over time. For CO_2 sensors without ABC, the year-to-year change tends to be negative. This would explain why overall, the CO_2 sensors tended to underreport CO_2 concentrations.

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13 In practice, this source of error will not result in DCV providing insufficient ventilation because Title 24 specified CO2 be maintained no more than 600 ppm above the outdoor air. However, this study considered it as a source of error because Title 24 now requires all CO2 sensors to display measured concentrations. There is some value in CO2 sensors that can provide accurate information to occupants.

Measurement errors were separated into two parts: zero offset and gain (even though the two may be counteracting one another and that sensor accuracy is a combined effect of the two). The study found that CO_2 sensors differ by manufacturer in terms of the estimated magnitude and sign of zero offsets and gains. The best performing CO_2 sensors have small zero offsets and gains. CO_2 sensors with ABC tended to have smaller zero offset in comparison to gain errors, which is expected since the intention of the ABC is to help maintain long-term stability. CO_2 sensors that do not have ABC have zero offset and gain errors that are of comparable magnitude. These findings are in general agreement with Fisk, Faulkner et al. (2009), who found that CO_2 sensors from some manufacturers had a better average accuracy, and sensors with a single lamp single wavelength design were generally associated with statistically significantly higher average accuracy.

One key limitation of this study is that it did not include a building that is occupied at all times which is the intended application for CO_2 sensors that use alternative technology (e.g. dual channel) to maintain long-term stability instead of ABC. Also, this study only evaluated sensor accuracy for two years, instead of the 5-year performance period specified in Title 24. All CO_2 sensors of a particular type were purchased at once, instead of buying them from different vendors and over time. Sensors manufactured from different batches at different times might have a more variable accuracy.

It is important to keep in mind that the reference CO_2 measurements used in this study to evaluate sensor accuracy are imperfect. The linearity of the reference CO_2 instrument was verified at least monthly throughout the two-year study period. The accuracy of the reference instruments was checked using calibration gases at multiple concentrations each time. While random errors on the scale of ±10 ppm are still likely, the data do not indicate systematic error in the reference CO_2 measurements that would change the main findings and conclusions of this study.

Conclusions

As a group, the seven CO_2 sensors evaluated in this study had better accuracy in the office and conference room settings, compared to prior results by Fisk, Faulkner et al. (2009). However, in the classroom environment where CO_2 concentrations were more variable with time, with higher peak concentrations, CO_2 measurement accuracy was similar to that as found by the prior study: 38 percent (at 700 ppm) and 44 percent (at 1,000 ppm) of sensors would have errors greater than ±75 ppm. In those cases, many CO_2 based DCV systems would fail to meet the design goals of saving energy while assuring that VRs meet code requirements. All CO_2 sensors evaluated in this two-year study were purchased new. They have not reached the 5-year performance period that is required by Title 24.

Findings from this study suggest that field checks of CO_2 sensor accuracy is needed. Ideally, two-point checks should be performed to improve accuracy because both zero offsets and gain errors can be important. Because many building managers may not have the skills and equipment necessary for field-based checks, it may be preferable to have the development of external companies that can provide high-quality checking of CO_2 sensor accuracy.

Substantial systematic changes in sensor accuracy were observed for a limited number of CO_2 sensors and in some study spaces during the two-year evaluation period; many other sensors had insignificant systematic changes in accuracy over time. This suggests that periodic replacement of CO_2 sensors used for DCV alone is not enough to guarantee accuracy. CO_2 sensors need to be checked for faults shortly after they are installed to ensure they are functioning properly. This might be accomplished by comparing multiple CO_2 sensors installed in a building in terms of daily trend and their measured values.

Accuracy of People Counters for Use in Controlling Building Ventilation

Objectives

MVRs per occupant are specified in MVR standards because they are considered useful, albeit imperfect, indicators of the adequacy of ventilation. Research has demonstrated that VRs per person are often predictive of occupant health and performance. Since VRs per person are useful metrics of the adequacy of ventilation, occupant counting can be considered as a tool, albeit imperfect, for better assuring the adequacy of ventilation while avoiding excess ventilation. Accordingly, this research task evaluated two commercially available occupant counting technologies, IR camera and IR beam counter, that could be used in DCV systems for commercial buildings. Occupant counting sensors are already being used in some buildings for other purposes, such as to count customers in retail stores, or count visitors to museums. This work evaluated accuracy in real world settings. Stress tests were also performed to identify scenarios that lead to counting errors.

Methods

Two occupant counting technologies purchased from a commercial vendor (Traf-Sys) were testing for their accuracy. The Irisys Gazelle IR camera was supplied with data processing software that reports the number of people entering and exiting the area being monitored. It can potentially count multiple people entering and exiting a doorway at the same time. The OmniCounter is a dual IR beam counter that can detect people entering and exiting a doorway. The counter is battery powered and can be mounted horizontally to give directional counts of people. The IR camera and IR beam were installed at two different types of doorways (Figure 29) where their performance was evaluated: (1) doorway to a 47-seat conference room that is used regularly for meetings and seminars, and (2) front entrance to a 4200 m^2 (45,000 ft^2) building that has 152 occupants. Both test locations are LBNL buildings. The LBNL Human Subjects Committee reviewed and approved this study.

The 72 m^2 (780 ft^2), 47-seat conference room was used regularly for meetings and seminars. It has a ceiling height of 2.74 m. The IR camera was mounted on the ceiling 1 m from the door. This distance was determined according to the ceiling height and the width of the door (0.89 m), following the setup instructions as explained in the user manual. The mixed-use (offices and laboratories) building front entrance has two sets of double doors. The interior doors have a total width of 1.82 m that swing outward into the vestibule. Following the user manual setup instructions, the IR camera was mounted 1.2 m from the door at a ceiling height of 2.74 m.

At both locations, the IR beam was mounted at a height of 1.12 m, roughly at the midpoint of the manufacturer's recommended range for mounting height (0.9 and 1.3 m). Prior to testing, an alignment procedure was performed according to the setup instructions as described in the user manual. The alignment procedure ensures that the IR transmitter and receiver were properly mounted.

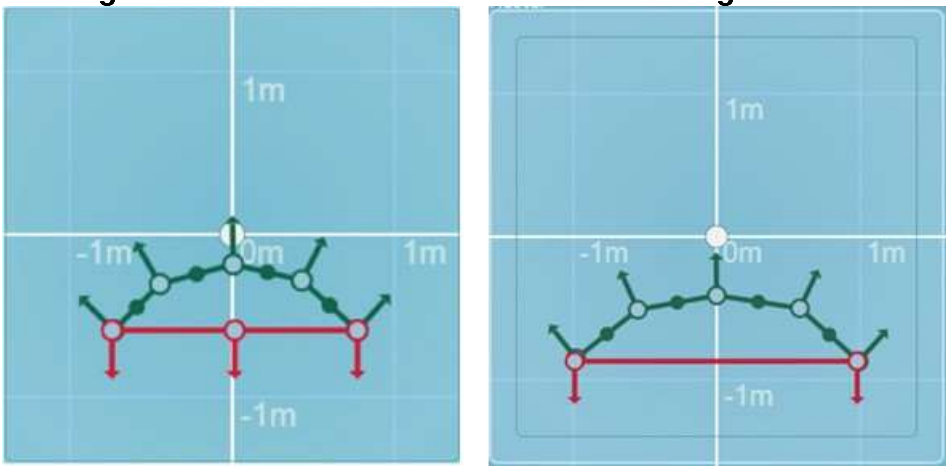
Figure 29: People Counters Tested at Two Different Doorways

(Left) IR camera installed in the doorway ceiling of a conference room. (Right) IR beam counter installed at a building entrance.

Source: Lawrence Berkeley National Laboratory

The IR camera software has a number of user adjustable settings. Figure 30 shows the counting lines specified in the software to give the in and out counts of people detected by the IR camera.

Figure 30: Infrared Camera Data Processing Software



In (green) and out (red) lines drawn in data processing software that the IR camera used to determine when a person enters or exits the conference room. The same shape was used for the conference room (left) and the building entrance (right).

Source: Lawrence Berkeley National Laboratory

A simple straight "out" line that extends the door width was sufficient for the IR camera to detect the movement of people exiting the room. However, after some trial-and-error, a curved "in" line resulted in less missed counts than a simple straight line. This is possibility because the IR camera can only view people inside the space that is being counted. This means the IR camera has a relatively short time to detect and track the movement of a person entering a space, in comparison to a person who is exiting the space that the camera can start tracking within its view from the doorway. An "in" line that curves inwards into the space gives the IR camera more time to detect people entering into the space, potentially resulting in fewer missed counts.

The IR camera user manual suggests walking testing to determine user adjustable settings that can affect how it interprets the heat source emitting from people as they walk underneath the camera. A "discrimination sensitivity" between 0 and 100 is used to adjust how the camera groups thermal objects together. At high sensitivity, the camera may see a person's arms and legs as separate thermal objects. At low sensitivity, the camera may group two people walking side by side as a single thermal object. After conducting walking tests at different sensitivity levels, a setting of 50 was selected for this study. The IR camera also has other advanced options designed to handle complex people movement in open spaces. For example, instead of counting people who cross the count line immediately, the software can be set to count only if the subject leaves the field of view. The software can also count a large object as two people walking close together, or join together many people entering the view at the same as one target group. In addition, a rapidly cooling or heating floor as a consequence of sun or wind exposure may be detected as a person by mistake. The IR camera software can perform an extra initialization step to avoid counting surfaces with temperature changes. For this study, no advanced option was selected.

The counting accuracy of the IR camera and IR beam were compared to reference counts determined by an observer. To assess accuracy of the observation and record keeping process, a second person recorded the number of people entering and exiting the doorway independently. Table 12 shows that accuracy of the observed counts is ±3 percent on average.

Table 12: Comparison of In and Out Counts of People by Two Observers

Date	Time	Direction	Counts by Observer 1	Counts by Observer 2	Percent Error
8/2	11:50 – 12:50	In	15	14	±3%
8/2	11:50 – 12:50	Out	20	20	0%
8/2	12:50 – 13:55	In	21	24	±7%
8/2	12:50 – 13:55	Out	26	29	±5%
8/3	9:50 – 11:00	In	42	38	±5%
8/3	9:50 – 11:00	Out	32	31	±2%
8/3	11:00 – 12:15	In	20	21	±2%
8/3	11:00 – 12:15	Out	34	36	±3%

Source: Lawrence Berkeley National Laboratory

The counting accuracies of the IR camera and IR beam were evaluated for 10 hours at the conference room collected over eight days when people entered the room to attend a seminar. Counting accuracies were evaluated for 13 hours at the building entrance over three days during mornings when people came to work, and also during lunchtime when people were going in and out of the building. In addition, the people counting technologies were evaluated using a series of scripted tests similar to those performed in a previous study by Fisk and Sullivan (2009).

1. One person walks through at a normal pace.
2. One person walks through at a very fast pace.
3. One person walks through at a normal pace with a cold winter coat with hood on.
4. One person walks through at a normal pace with a room temperature winter coat with hood on.
5. One person walks through at a normal pace with covered coffee cup with hot coffee.
6. One person walks through at a normal pace with open coffee cup with hot coffee.
7. One person walks through at a normal pace, with a warm laptop computer held flat to the ground.
8. Two people walk through at a normal pace, second person follows first as close as comfortable.

9. Three people walk through at a normal pace, one after another as close as comfortable.
10. Four people walk through at a normal pace, one after another as close as comfortable.
11. One person enters and simultaneously a second person exits.
12. Two persons enter and simultaneously two persons exit.
13. Three persons enter and simultaneously two persons exit.
14. Two people walk through at a normal pace, side by side.

Results

Scripted Tests

Both people counting technologies performed well, on average, during scripted tests with only one person walking through the doorway. The average counting error was 1 percent (range -8 percent to 5 percent) for the infrared (IR) camera based system, and 3 percent (range -18 percent to 45 percent) for the IR beam based system, when one person walked through at normal or fast pace without wearing a winter jacket or carrying anything. Detailed results are tabulated in Appendix D.

Figure 31 shows examples of thermal images taken using a Fluke TiR32 camera during some of the scripted tests. Tests involving wearing a winter coat, carrying a cup of coffee or laptop, should only affect the performance of the IR camera, if at all, because those conditions may interfere with the identification of people as thermal objects. The IR camera had a slightly higher counting error (5 percent, range -17 percent to 50 percent) than the IR beam (1 percent, range -10 percent to 25 percent) during these scripted tests involving a winter coat or the person carrying either a cup of coffee or a laptop.

Figure 31: Thermal Images Taken During Scripted Tests

(a) Person wearing a cold winter jacket with hood on, (b) wearing a room temperature winter jacket with hood on, (c) carrying a cup of uncovered hot coffee, and (d) carrying a warm laptop. The temperature of hot coffee was 82°C (180°F), measured using a thermometer. When uncovered, the hot coffee cooled slightly to 74 to 78°C (166 to 172°F). The winter coat was cooled to 3 to 7°C (38 to 45°F) by placing it in a freezer. The temperature of the warm laptop that had been running for several hours was between 28 and 41°C (82 to 105°F).

Source: Lawrence Berkeley National Laboratory

Walking pace of the person did not appear to affect counting error for either technology. In scripted tests, the walking speed at a normal pace was 0.5 to 1.1 m/s. At a fast pace, the walking speed increased to 0.6 to 1.6 m/s. There was one period with much poorer accuracy of the IR beam system. The reason for the poorer accuracy is not known. Differences in walking style of the person being counted in these scripted tests may explain the variability in the results.

In scripted tests involving two or more people, both people counting technologies performed well when people walk one after another. The counting error was -3 percent for both technologies on average for those tests (range -27 percent to 8 percent for IR camera, range -9 percent to 8 percent for IR beam). However, the IR beam could not give an accurate count when multiple people entered and exited the doorway at the same time. The average counting error was -44 percent (range -70 percent to 0 percent), meaning that IR beam undercounted the number of people entering and/or exiting because the sensor could not resolve breaking of the beams by multiple people at the same time. On the other hand, the IR camera performed well in those scenarios. The average counting error was -7 percent (range -40 percent to 26 percent).

Unscripted Tests

In unscripted tests, IR camera tend to slightly over-count the number people entering and exiting by 6 percent on average, whereas IR beam tend to slightly under-count by 14 percent on average. The average number of In + Out counts per hour that occurred at the two test locations was 55 (conference room) and 38 counts per hour (building entrance). Counting errors on the order of 10 percent on average and higher in some situations are consistent with results from prior testing of people counters (Fisk and Sullivan 2009, Kuutti, Blomqvist et al. 2014).

An example that resulted in IR camera over-counting is when a person swings his/her arms when entering or exiting the door at a fast pace. The IR camera would detect the swinging motion as two or more people, instead of one. Another example is when a person paused for a moment as s/he entered into the room, and stepped backward slightly to decide where to sit in a conference room. In doing so this person may cross the counting lines set in the IR camera software multiple times, resulting in over-counting.

The building entrance appeared to be a more challenging test location than the conference room. For example, the IR camera would count items such as shopping bags and carryon luggage that people brought to work as an extra in count. This resulted in over-counting of the people entering into the building. In contrast, people tend to carry fewer large items to a conference room when attending a meeting or presentation. The IR beam tends to undercount if multiple people exit the double door at the same time. This was observed at the building entrance as people were leaving the building together as a group. At the conference room with a single door, people tend to enter or exit one after another, instead of walking through the door together.

If people counters were used to control DCV, the estimated number of occupants inside a space would be the output that signals the need for more or less ventilation. Table 13 shows the average number of occupants inside either the conference room or the office/laboratory building by subtracting the out count from the in count, calculated at a 5-minute time interval. Note that the office/laboratory building has multiple entrances, so there are more occupants inside the building than what is suggested by the numbers shown in Table 13.

The IR camera undercounted the average number of people in a space by 1 (-9 percent error), and overcounted the peak number of people by 0.6 (3 percent error). The IR beam overcounted the average number of people in the space by 0.1 (1 percent error), and undercounted the peak number of people by 0.2 (error -1 percent error).

Figure 32 shows the error in counts of the average number of occupants determined using signals from the IR camera and IR beam, plotted as a function of the average number occupants observed inside the two study spaces. The scattered plot shows that counting error appears to be insensitive to the number of occupants inside a study space. This suggests that even though the IR camera and IR beam were evaluated at two test locations that were occupied by a relatively small number of occupants (mean N_{occ} = 11.3) during a given study period, the resulted counting errors may apply to spaces that are occupied by more people. More testing of the performance of people counters in larger spaces with more occupants is needed to confirm this hypothesis.

Table 13: Average Number of Occupants Counted Inside Conference Room

Test	N_{occ} Observed	N_{occ} IR Camera	N_{occ} IR Beam	ΔN_{occ} IR Camera	ΔN_{occ} IR Beam
1	21.8	21.4	21.2	-0.4	-0.6
2	14.4	11.8	12.8	-2.7	-1.6
3	7.4	4.2	7.9	-3.3	0.5
4	9.6	8.5	8.7	-1.1	-0.9
5	11.1	11.2	11.3	0.1	0.2
6	6.8	6.8	7.4	0.1	0.6
7	18.7	17.1	20.0	-1.6	1.3
8	21.5	31.1	21.4	9.6	-0.1

N_{occ} = average number of occupants; ΔN_{occ} = change in average number of occupants.

Source: Lawrence Berkeley National Laboratory

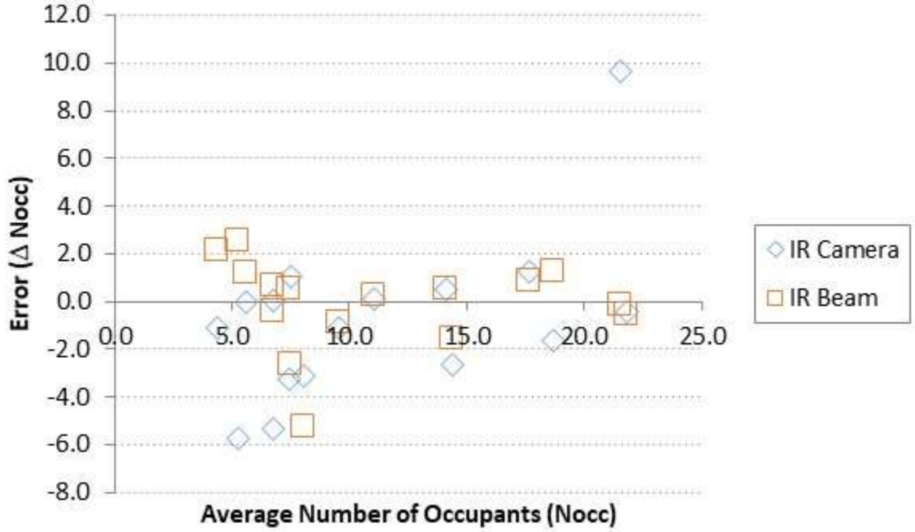
Table 14: Average Number of Occupants Counted Inside Building Entrance

Test	N_{occ} Observed	N_{occ} IR Camera	N_{occ} IR Beam	ΔN_{occ} IR Camera	ΔN_{occ} IR Beam
1	7.5	8.6	4.9	1.1	-2.6
2	5.6	5.6	6.8	-0.1	1.2
3	14.2	14.7	14.7	0.5	0.5
4	4.4	3.3	6.6	-1.1	2.2
5	5.3	-0.5	7.8	-5.7	2.5
6	17.7	19.0	18.5	1.3	0.9
7	8.0	5.0	2.8	-3.1	-5.2
8	6.7	1.4	6.3	-5.3	-0.4

N_{occ} = average number of occupants; ΔN_{occ} = change in average number of occupants.

Source: Lawrence Berkeley National Laboratory

Figure 32: People Counting Errors as Function of Average Observed Occupancy

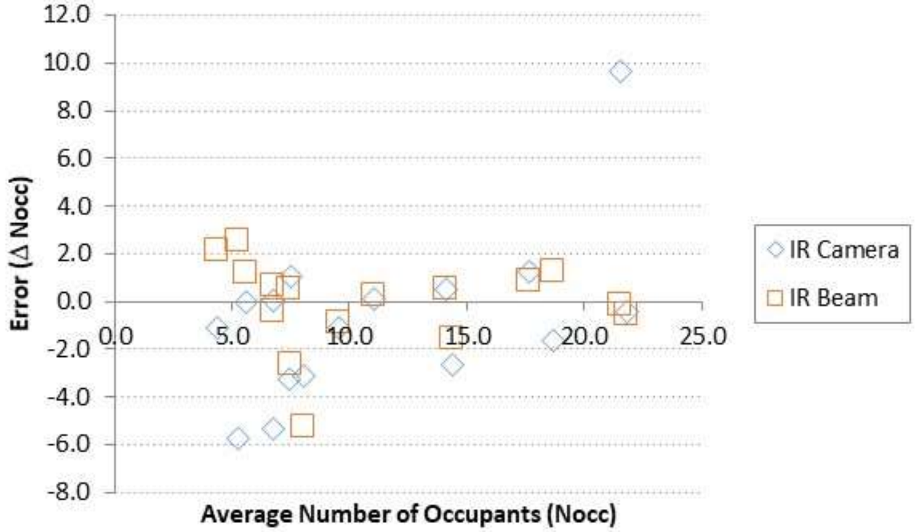


Error in counts of the average number of occupants (Δ N_{occ}) determined using signals from people counters, plotted as a function of the average number of occupants observed (N_{occ}) at the two test locations.

Source: Lawrence Berkeley National Laboratory

The California Title 24 code (CEC 2013) requires outdoor air ventilation be provided at a minimum rate of 15 cubic feet per minute (CFM) (7 liters per second [L/s]) per person or 0.15 CFM (0.7 L/s) per ft^2 of floor area for most commercial buildings, whichever is higher. The required outdoor air supply rate is calculated at each 5-minute time interval using the number of occupants determined by the people counters. Figure 33 and Figure 34 compare the average VRs that would be provided to the study spaces based on people counters, and the VRs that would be provided based on the observed true counts of people. Because relatively few occupants passed through the building entrance, for illustrative purpose, the researchers assumed a smaller building volume of 250 m^3 (1,000 ft^2 floor area) and a reduced per floor area requirement of 50 CFM. This adjustment is needed so that the predicted CO_2 concentrations are in the typical range for office buildings (700 ppm), instead of barely above the outdoor level of 400 ppm had the whole building volume been used for this analysis. The choice of a reduced per floor area requirement allows the comparison of VRs be more dependent on the number of occupants inside the space. For the conference room, the actual room volume (200 m^3) and the corresponding per floor area ventilation (117 CFM) was used.

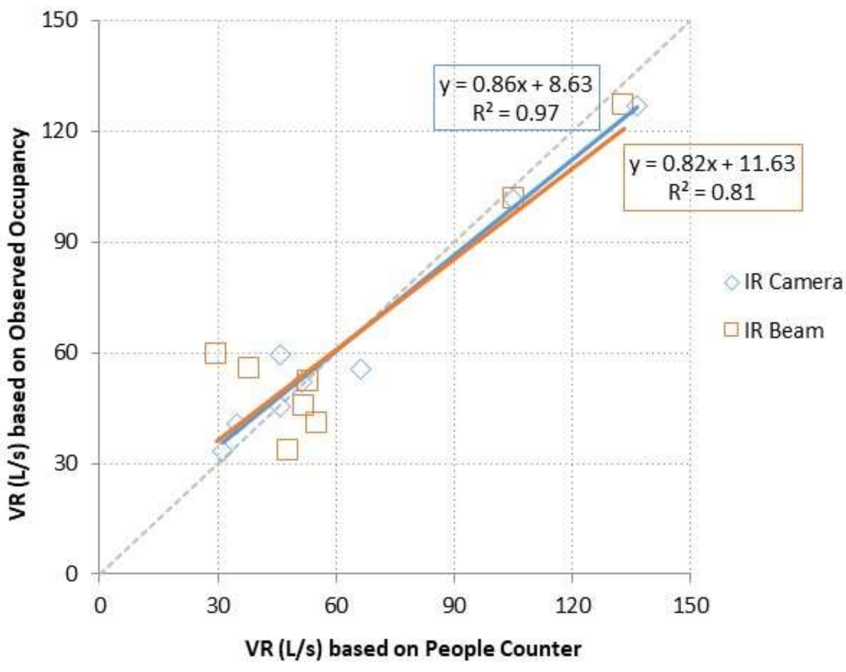
Figure 33: Average Ventilation Rates Based on Conference Room People Counts



Comparison of the average ventilation rates based on the number of occupants in the room as determined by the people counters, and the observed true counts in a conference room.

Source: Lawrence Berkeley National Laboratory

Figure 34: Average Ventilation Rates Based on People Counts Measured at Building Entrance



Comparison of the average ventilation rates based on the number of occupants in the room as determined by the people counters, and the observed true counts at the building entrance.

Source: Lawrence Berkeley National Laboratory

Overall, Figure 33 shows that the IR beam performed slightly better than the IR camera for the conference room, as indicated by the higher R^2 value and slope ~1, for the study periods considered. However, the IR beam performed worse (lower R^2 value) than the IR camera for the building entrance (Figure 34). This is largely because the IR beam would miscount when multiple people enter or exit as a group through the double door, as pointed out earlier.

Table 15 and Table 16 show the differences in VR that would be provided to the study space if the number of occupants was determined by the IR camera and IR beam with respect to the required VR based on the observed true counts of people. On average, both IR camera and IR beam would give unbiased signals if used to control building ventilation. The mean difference in average VR provided to the study spaces with respect to VR based on the observed true counts is near zero.

Table 15: Difference in Average Ventilation Rate Based on People Counts (Conference Room)

Test	L/s Based on Observed Occupancy	Δ L/s (percent error) IR Camera	Δ L/s (percent error) IR Beam*
1	160	-3 (-2%)	-5 (-3%)
2	109	-16 (-15%)	-10 (-9%)
3	67	-9 (-14%)	-1 (-2%)
4	75	-6 (-8%)	-5 (-7%)
5	94	1 (1%)	1 (1%)
6	60	0.5 (1%)	5 (8%)
7	146	-10 (-7%)	12 (8%)
8	164	67 (41%)	-0.4 (-0.2%)
	MeanΔL/s	3	-0.4
	MeanΔL/s|	14	5

L/s = Liters per second. *Better-performing technology for the study space.

Source: Lawrence Berkeley National Laboratory

Table 16: Difference in Average Ventilation Rate Based on People Counts (Building Entrance)

Test	L/s Based on Observed Occupancy	Δ L/s (percent error) IR Camera*	Δ L/s (percent error) IR Beam
1	56	11 (19%)	-17 (-31%)
2	45	0.4 (1%)	7 (15%)
3	102	4 (3%)	4 (4%)
4	33	-2 (-5%)	15 (45%)
5	41	-6 (-14%)	15 (36%)
6	127	9 (7%)	6 (5%)
7	60	-14 (-23%)	-30 (-50%)
8	52	-1 (-2%)	1 (2%)
	MeanΔL/s	0.3	-0.04
	MeanΔL/s|	6	12

L/s = Liters per second. *Better-performing technology for the study space.

Source: Lawrence Berkeley National Laboratory

Table 15 shows that the use of IR beam is more suitable at the entrance to the conference room, as indicated by a lower mean absolute difference of 5 L/s, compared to 14 L/s when the IR camera was used. At the building entrance, the IR camera performed better. If the better-performing technology is used for the respective doorways, the people counters would result in a mean absolute difference of roughly 5 L/s of the required VR. The corresponding percentage errors are about ±10 percent if IR beam is used at the conference room, and ±20 percent if IR camera is used at the building entrance. The larger percentage errors calculated for the building entrance is partly because of the lower occupant density compared to conference room, resulting in lower required VR: average of 64 L/s for the building entrance, compared to 109 L/s for the conference room.

Indoor CO_2 concentrations were calculated as a metric to evaluate the potential impacts on indoor air quality if VRs were provided to the study spaces based on the number of occupants determined by the people counters. CO_2 concentrations, C(t), were calculated in the two study spaces at a time-step of t = 5 minutes using the following equation.

$$C(t) = C_{out} + [E/Q][1-\exp(-Q/V*t)] + [C(t_0) - C_{out}][\exp(-Q/V*t)]$$

where C_{out} is the outdoor CO_2 concentrations assumed to equal 400 ppm, E is the CO_2 emission rate determined by the observed number of occupants in the room times 0.0052 L/s CO_2 per person (ASHRAE 2013), Q (m^3/s) is the VR determined either by the observed true counts or based on people counting technologies, V (m^3) is the air volume of the study space, and $C(t_0)$ is the indoor CO_2 concentrations from the previous time step. The initial indoor CO_2 concentration was set to equal 400 ppm for this analysis.

Table 17 and Table 18 show the predicted average CO_2 concentrations in the study spaces if the VR is provided based on the true counts of number of occupants, and if the VR is provided based on data from the people counters. If the better-performing people counting technology is used for the respective study spaces (i.e. IR beam at the conference room, and IR camera at the building entrance), the difference in average CO_2 concentrations in the study space due to counting errors would be small (±25 ppm). This small difference in predicted CO_2 suggests that using people counters to control ventilation would likely result in indoor air quality that is not notably different from what would occur if the true occupant counts are known.

Table 17: Predicted Average Carbon Dioxide Concentrations in Conference Room

Test	Average CO_2 (ppm) Observed	Average CO_2 (ppm) IR Camera	Average CO_2 (ppm) IR Beam	Δ Avg. CO_2 (ppm) IR Camera	Δ Avg. CO_2 (ppm) IR Beam*
1	921	931	932	10	11
2	822	857	845	36	24
3	673	688	673	15	0
4	692	701	701	9	9
5	765	762	763	-3	-2
6	660	659	650	-1	-10
7	806	828	784	21	-22
8	842	727	840	-114	-2

***Better-performing technology for the study space.**

Source: Lawrence Berkeley National Laboratory

Table 18: Predicted Average Carbon Dioxide Concentrations in Building Entrance

Test	Average CO_2 (ppm) Observed	Average CO_2 (ppm) IR Camera	Average CO_2 (ppm) IR Beam	Δ Avg. CO_2 (ppm) IR Camera*	Δ Avg. CO_2 (ppm) IR Beam
1	724	700	778	-25	53
2	555	555	549	0	-6
3	747	741	739	-6	-8
4	602	605	584	3	-18
5	690	706	656	16	-34
6	764	748	754	-16	-10
7	697	720	771	24	75
8	826	833	819	7	-7

***Better-performing technology for the study space.**

Source: Lawrence Berkeley National Laboratory

Discussion

The accuracy specification of CO_2 sensor for DCV use is approximately ±10 percent. The two people counting technologies on average had errors typically less than 10 percent indicating that people counters will often be sufficiently accurate for DCV. However, there were times when the technologies reported people counts with errors outside of the ±10 percent range. Thus, periods of over- and under-ventilation relative to the targeted values may result if people counters were used for DCV.

Occupancy counters differ from CO_2 sensors in their temporal response to a change in occupancy. The occupancy counter responds immediately when a person enters or exits a space, while a CO_2 sensor responds to the change in CO_2 concentration which occurs slowly over a period of about one to three hours after a change in occupancy or a change in VR. Although standards for minimum VRs specify minimum rates per occupant, the temporal lags of CO_2-based DCV may be considered desirable since the purpose of DCV is to maintain acceptable indoor levels of occupant-generated air pollutants as occupancy or occupant activity level varies. If desired, it should be relatively easy to program temporal lags into the control algorithms for DCV systems using people counters. The lag time would be based on estimates of the air change time constant, that is, the rate at which contaminant levels adjust to a change in VR or occupancy. If activity levels are known, control algorithms could also account for activity levels, although not with real-time modulation. However, the research team is not aware of any actual instances when control algorithms for DCV based on people counts have adjusted for the temporal lags or activity levels.

Title 24 specifies that at least one CO_2 sensor be installed per 10,000 ft^2 (930 m^2) of floor space. People counters may be economically favorable for DCV relative to CO_2 sensors for some building layouts. For example, buildings with an open floor plan and a limited number of doorways will need only a small number of people counters to determine the number of occupants. However, more CO_2 sensors may be needed to properly measure the indoor concentration due to spatial differences inside the space. An additional benefit of monitoring people counts is that occupancy data for many spaces like retail stores, museums, and libraries may be useful for purposes other than DCV. CO_2 concentration data collected for DCV have fewer synergetic uses other than for controlling building ventilation.

Title 24 requires CO_2 sensors be certified by manufacturers for their accuracy for five years. Presumably, CO_2 sensors will need to be calibrated or replaced after that. The performance of people counters over time is unknown. The overall cost of using people counters for DCV would depend on the stability of the counting accuracy of the technology over its useful life.

Conclusions

Two people counting technologies, IR camera and IR beam, were evaluated for their suitability for DCV. The IR beam sensor is only suitable for spaces with single-wide doors, such as an interior door to a conference room. For most commercial buildings with double doors to the exterior, an IR camera is likely needed to provide reliable occupant counts. Use of the IR beam people counter would result in ±10 percent of the required ventilation in the conference room. Use of the IR camera counter would result in ±20 percent of the required VR in the building with a double-door entrance.

For both test locations, the predicted average CO_2 concentrations in the space would deviate by roughly ±25 ppm from the concentrations expected with perfectly accurate people counting. On average, the use of these people counters to control the VR would result in indoor CO_2 concentrations within the ±75 ppm accuracy range specified by Title 24 for CO_2 sensors. However, when used at the building entrance—the more challenging location to accurately monitor people counts—an error of ±20 percent of the required VR may not be acceptable to meet the energy saving goals of DCV.

Further considerations of costs and long-term performance of people counters are needed for the recommendation of this technology for use with DCV. Implications of people counting error leading to over- and under-ventilation and the resulted energy costs will need to be modeled using simulation tools such as EnergyPlus. More thorough testing of people counting technologies should also be conducted in other types of buildings where the movement of people may be different from those encountered in this study.

Method for Measuring Building Ventilation Rate Based on Measured Carbon Dioxide and Occupant Counts

Objectives

A transient mass balance model was applied to calculate VRs using CO_2 concentration and people counts measured in two office spaces for approximately two weeks. This method does not require an assumption that occupancy and VR are steady for a sufficient period of time for indoor CO_2 concentrations to reach equilibrium. The proposed transient method of determining VRs has the additional advantage of including air infiltration, and can be performed at relatively low cost, especially in spaces where occupancy is already known. The accuracy of the estimated VR using this transient method was determined by comparing with VR measured using tracer gas decay as the reference.

Methods

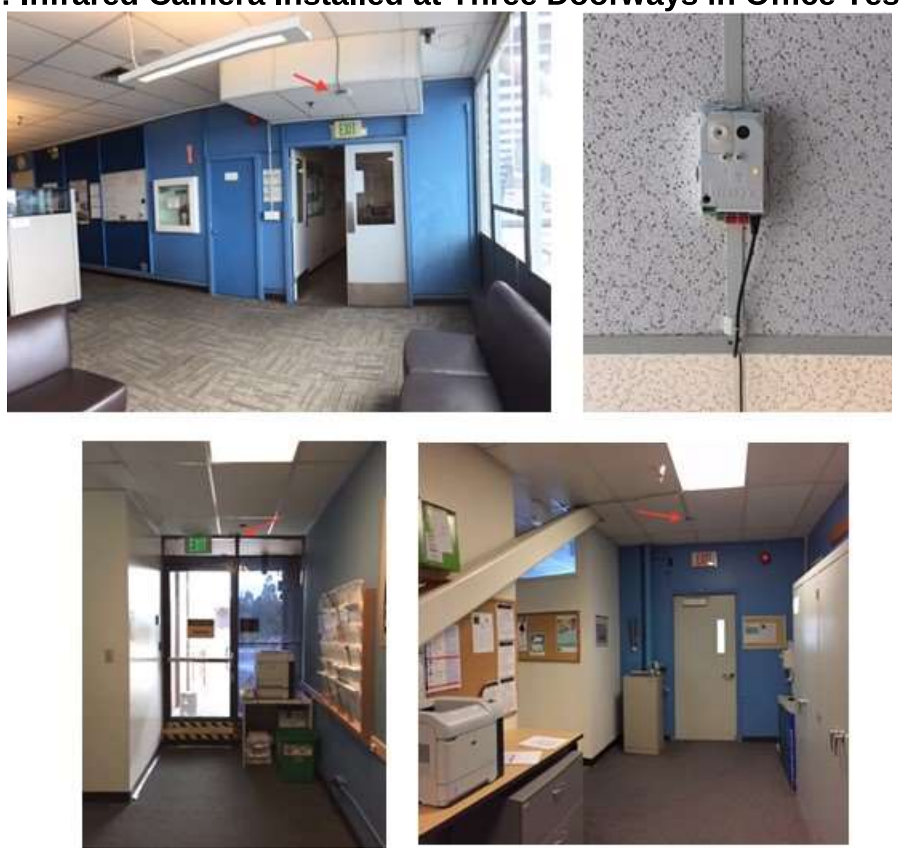
People Counters Installed in Two Office Spaces

The IR camera was installed in two study office spaces (see Appendix E for floor plan). The office test space 1 is 1,060 m^2 (11,400 ft^2) with 2.8 m ceiling height (9 ft) located on the top floor of a 4-story LBNL office building. Occupied areas within the space include private and open offices for 73 occupants and three conference rooms. The largest conference room can hold 30 people and the two smaller conference rooms can hold 12 and 8 people respectively. Two rooftop HVAC units served this study space. The facility manager of the office space reported that economizers were likely not functioning because of the age of the equipment (these units are being replaced shortly after completion of this work). VRs measured using a CO_2 decay test (see Appendix E) confirmed the facility manager's report. CO_2 decay rates measured on two days under very different weather conditions suggested the same VR of approximately 1.6 h^{-1}((air changes per hour).

There are three entrances into this office space (Figure 35). An IR camera (Irisys Gazelle 60-degree lens, the same model as evaluated in the previous task of this project) was installed at each entrance. The research team set up the IR camera using the data processing software to record the number of people entering and exiting each of the entrances at a 15-minute time interval. All entrances met the height requirement of 2.4 to 4.3 m (8 to 14 ft) for installation of the IR camera. One entrance (Figure 35, top left) had a drop ceiling (height = 2.4 m), which limited the door width that could be monitored to 1.2 m per the manufacturer's installation guide. This entrance had a double door that is 1.5-m in width that would have been too wide for the IR camera to fully capture the movement of people. But because occupants use only one side of the door, as shown in Figure 35 (top left), the width of the doorway (0.75 m) is within the dimension that can be monitored using the IR camera. The other two entrances had a ceiling height of 2.8 m and can monitor a doorway up to 1.6 m in width, which is more than enough for the singlewide door that has a width of 1 m (Figure 35, bottom row).

User adjustable parameters, such as drawing the "in" and "out" lines to increment counts as people cross them in the IR camera data processing software, were specified by the research team after some trial and error. The research team observed the movement of people at each monitored doorway to make sure that the IR camera and data processing software captured occupant counts accurately. For example, researchers found that the IR camera at the entrance located next to west-facing windows (Figure 35, top left) was likely affected by the afternoon sun shining directly on the area being monitored. Window shades were therefore closed in the afternoon during the two-week study period to improve counting accuracy.

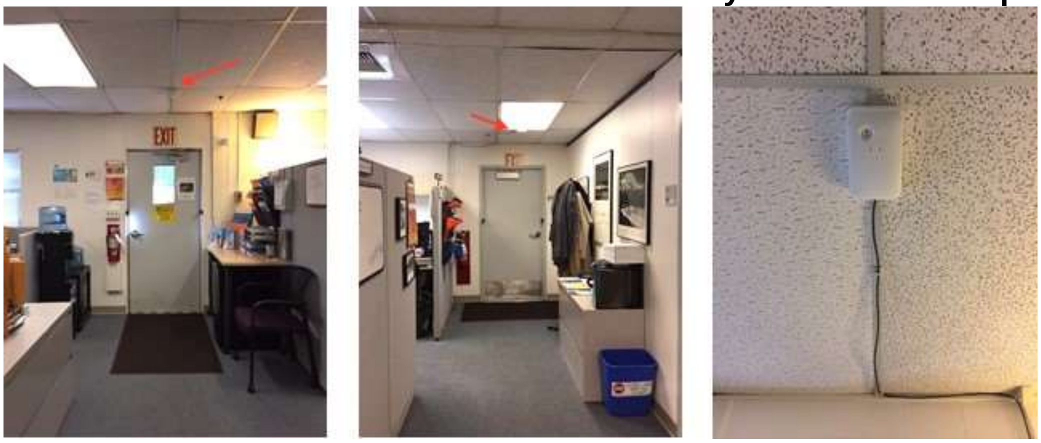
Figure 35: Infrared Camera Installed at Three Doorways in Office Test Space 1



Source: Lawrence Berkeley National Laboratory

The office test space 2 (Figure 36) is a small, 192 m^2 (2,067 ft^2) office trailer with a ceiling height of 2.4 m (8 ft). According to the manufacturer's installation guide, this relatively low height means the IR camera can only be used if the doorway is less than 1.2 m wide. The two singlewide doors in office space 2 met this door-width installation limit. Office space 2 is served by two wall-mount HVAC units without economizers. Appendix E shows the floor plan of this small office space that is occupied by 15 people.

Figure 36: Infrared Camera Installed at Two Doorways in Office Test Space 2



Source: Lawrence Berkeley National Laboratory

CO_2 decay tests conducted in office space 2 on two days with very different weather conditions suggested the same VR of approximately 1.6 h^{-1}. Table 19 summarizes the VRs determined from the CO_2 decay tests (see Appendix E for more detail). The per-person VR for office space 2 was calculated assuming N = 15. For office space 1, the per-person VR was calculated by summing the number of office occupants (N = 73) and assuming the conference rooms are at half capacity (N = 25). The per floor area VRs at the two study spaces were calculated by dividing the volumetric outdoor airflow rate by the floor area. Under these assumptions, the two study spaces had similar VRs that exceeded California's Title 24 requirements: >7.5 L/s-person (or 15 CFM/person) and >0.75 L/s-m^2 (or 0.15 CFM/ft^2).

Readings from the IR camera were compared with manual observations. The research team counted the number of occupants several times a day, typically once in the morning (between 8 a.m. and 11 a.m.), once in the early afternoon (11 a.m.–2 p.m.), and once in the afternoon (2 p.m.–5 p.m.). If a conference room had a closed door at the time of manual counting, the number of occupants inside the conference room were estimated using the number of attendees reported in the room reservation on the shared Google calendar. For private offices with a closed door, the research team assumed that half were occupied when estimating the number of people at the time of manual observation.

Table 19: Ventilation Rate Calculated from Carbon Dioxide Decay Tests

	Office Test Space 1	Office Test Space 2
Ventilation Rate	1.6 h^{-1}	1.6 h^{-1}
Per Person Ventilation Rate	13 L/s-person (29 CFM/person)	14 L/s-person (29 CFM/person)
Per Floor Area Ventilation Rate	1.2 L/s-m^2 (0.24 CFM/ft^2)	1.1 L/s-m^2 (0.21 CFM/ft$^{2)}$

Source: Lawrence Berkeley National Laboratory

The data processing software recorded the number of people entering (N_{in}) and exiting (N_{out}) the space every 15 minutes. The number of occupants at a given time is determined by adding $\Delta N = N_{out} - N_{in}$ to the value of N from previous time steps. This calculation would sometimes lead to a negative number of occupants. To obtain a usable number of occupants for calculating the VR using the transient model, N is set to 0 if adding ΔN to the value from previous time step would result in a negative number. This straightforward way of determining number of occupants from N_{in} and N_{out} also resulted in both negative and positive counts of occupants when the offices were unoccupied at night and on the weekend. To avoid propagating counting errors from one day to another, N was reset to 0 every morning at 2 a.m.

Carbon Dioxide Measurements

CO_2 concentrations were monitored at a central location in the larger office space 1 using an EGM4 gas analyzer, and in the smaller office space 2 using a newly purchased and calibrated Vaisala GMW94 CO_2 sensor. CO_2 concentrations were monitored at one-minute intervals during the two-week study.

In addition, CO_2 concentrations were measured at other locations in the study spaces to see if concentrations were well mixed. Appendix E shows the difference between CO_2 concentrations measured at the different locations with respect to the central location. The comparison suggests that CO_2 concentrations were well mixed within the main area of office space 1. The large 30-seat conference room had CO_2 concentrations above the levels measured at the central location. This is a source of error when the transient model is applied to office space 1 by treating it as a single well-mixed zone. The two smaller conference rooms had CO_2 concentrations more similar to the levels measured at the central location.

On average, CO_2 concentrations measured inside the two smaller conference rooms were slightly lower than the levels measured at the central location. This could be a result of opened windows. Occupants were asked to keep windows closed during the two week study, but the research team observed window opening both in conference rooms and in private offices on several occasions during manual counts.

About half of the occupants in the smaller office space 2 have a private office. The research team observed that doors were often kept closed. This may explain slightly higher CO_2 concentrations being measured in one private office, in comparison to the general area. Deviations from the well-mixed assumption are likely a source of error when applying the transient method.

Calculation of Ventilation Rates

A transient method was applied to calculate the VRs using CO_2 and people count measurements collected from the two office spaces. The mass balance model was solved by using a nonlinear least square fit function (R statistical software) to determine the value of Q (m^3/h).

$$C(t) = C_{out} + \frac{G}{Q}\left(1 - e^{-\frac{Q}{V}t}\right)$$

where G (L/h) is CO_2 generation rate, V (m^3) is air volume of the space, $C(t)$ is CO_2 concentration indoor at time t, and C_{out} is CO_2 concentration outdoor. Persily and de Jonge (2017) suggested an average CO_2 generation rate of 0.0048 L/s-person for office workers, based on updated understanding of human metabolism and exercise physiology, obtained using body mass and activity data of adults (ages 21 to 60, 50 percent male and 50 percent female, 1.4 met). G is calculated by multiplying 0.0048 L/s-person and the number of occupants estimated every 15 minutes from IR camera. $C(t)$ is the 5-minute averaged indoor CO_2 concentrations at the end of each 15-minute time interval. C_{out} was not monitored; instead it is estimated using the mean indoor CO_2 measured between 2 and 5 am, when the study space is unoccupied.

The default algorithm (Gauss-Newton) used by the nonlinear least square fitting with an initial guess of one air change per hour (i.e. Q/V = 1/h) resulted in quick convergence for this study. Batterman (2017) compared different methods to estimate classroom VRs using different methods: steady-state, build-up, decay, and transient mass balance. The last of the four methods of Batterman is the same as the method applied here.

For comparison, VRs were also estimated using the steady-state method.

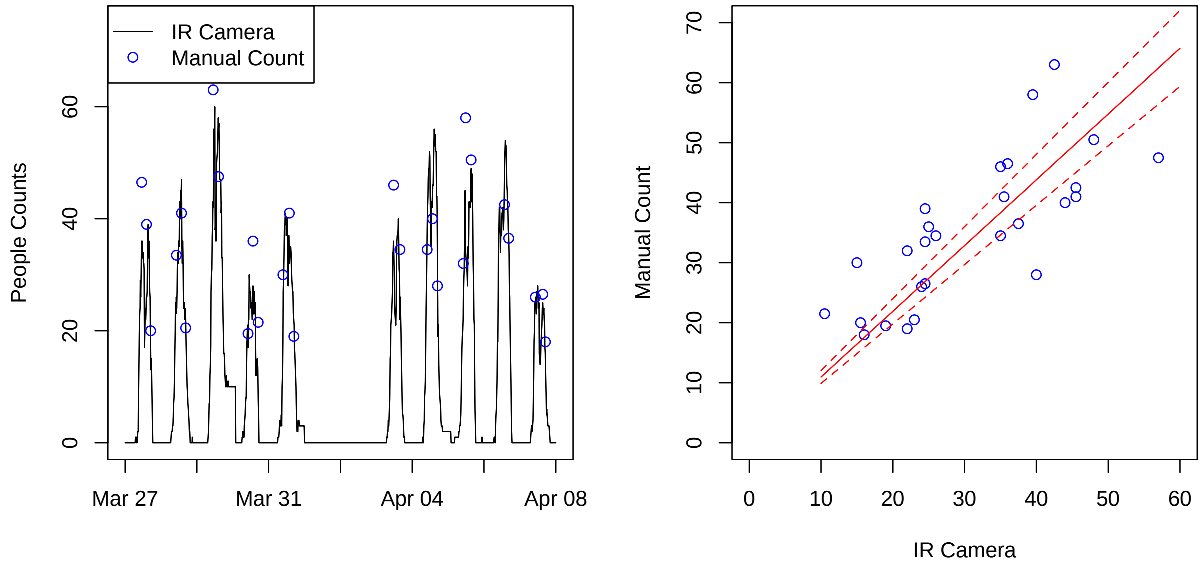
$$Q = G_{max}/(C_{max} - C_{out})$$

where G_{max} is CO_2 generation rate calculated using the maximum 1-hour average number of occupants, and C_{max} is the maximum 5-minute average indoor CO_2 concentrations. Time series plots of CO_2 and people counts measured in the two study spaces are provided in Appendix E. Even though the times when G_{max} and C_{max} happened may not be concurrent, CO_2 and people counts generally showed a similar trend over time, with values increasing in the morning as people arrived to work, a drop in values during lunch hour, followed by a subsequent increase in values as people returned to work from lunch, finally values begin to drop as people left work in the afternoon.

Results

Figure 37 compares the number of occupants determined using the IR camera in office space 1 with manual observations. The scatter plot (Figure 37, right) shows result from linear regression obtained by forcing the intercept to equaled 0: slope = 1.1 (standard error = 0.05), R^2 = 0.46.

Figure 37: Office Test Space 1 Occupancy, Infrared Camera Compared to Observed

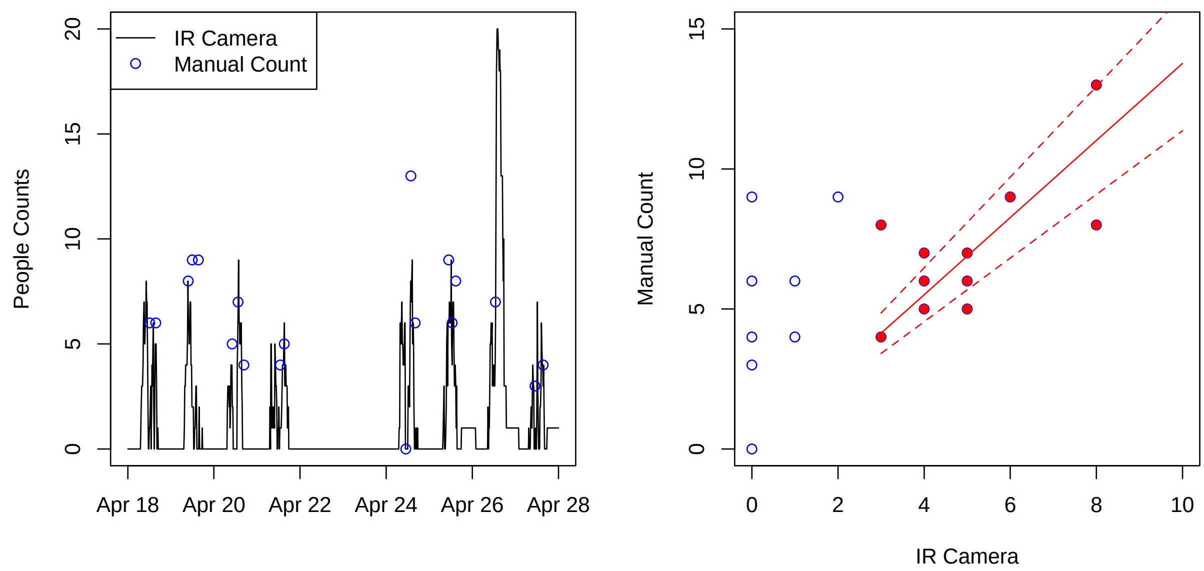


The red line is the best-fit estimate from linear regression. The dotted lines shows the 95 percent confidence interval of the best-fit estimate.

Source: Lawrence Berkeley National Laboratory

Figure 38 shows a similar set of results for office space 2: slope = 1.4 (standard error = 0.1), R^2 = 0.41. The research team observed that IR camera tended to under-count number of people entering into the space. In comparison, the IR camera counted the number of people exiting the space with higher accuracy. Because the IR camera is positioned inside the space, it has a better view of a person leaving the space than a person entering into s apace. For the smaller office space 2, a meaningful slope can only be obtained when comparing with manual observations if the IR camera recorded at least 3 occupants in the space (as indicated by data points colored in red). Because of the method used to avoid getting negative occupant counts, incidences when IR camera showing zero occupants occurred during times of large counting errors. As a general rule, people counts obtained from subtracting N_{out} from N_{in} are inherently more uncertain when the total number of occupants in a space is small. This is evident from the data collected from office space 2.

Figure 38: Office Test Space 2 Occupancy, Infrared Camera Compared to Observed



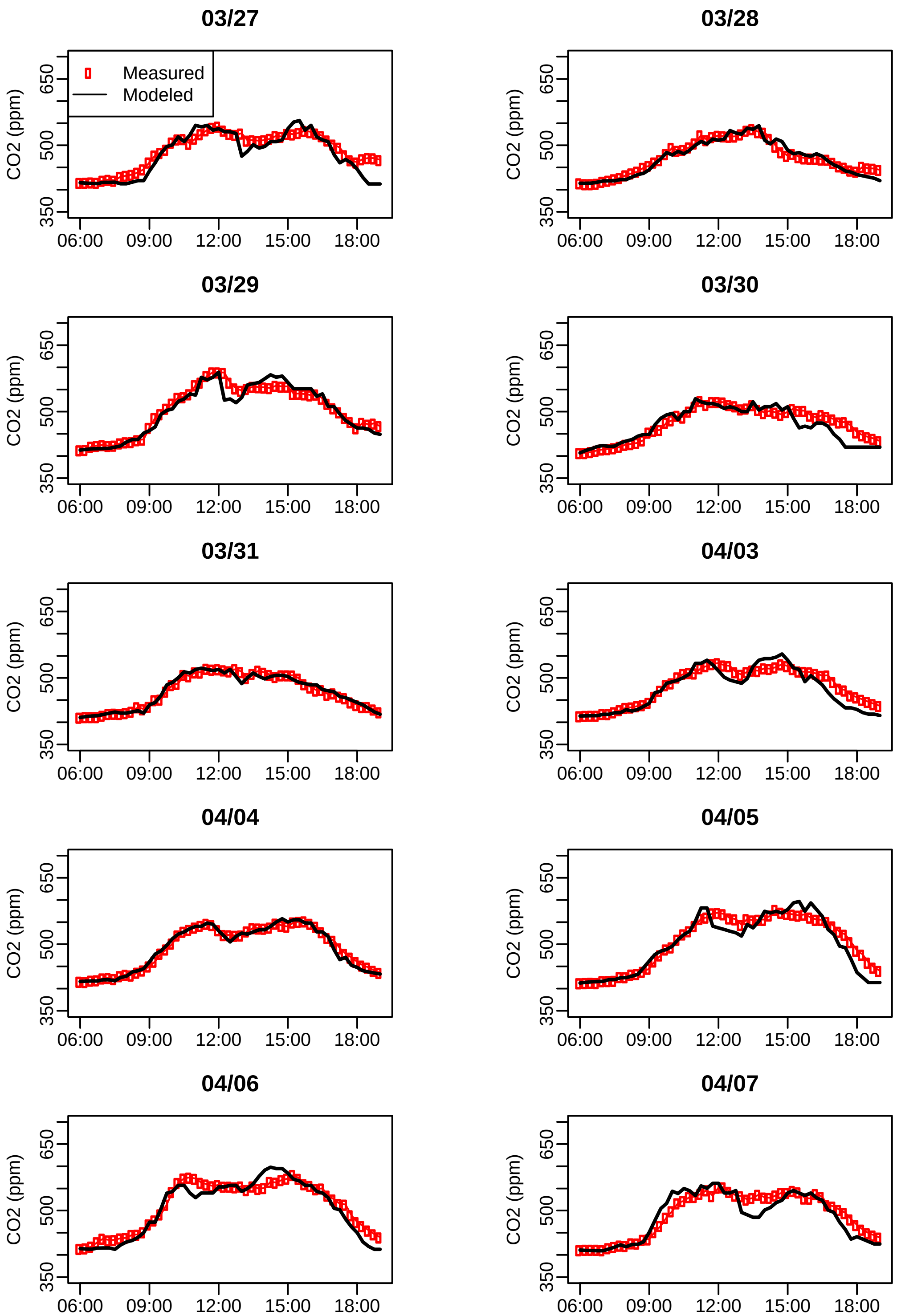
Linear regression (right) only used data points colored in red (i.e. IR camera gave occupant counts ≥3). The red line is the best-fit estimate from linear regression. The dotted line shows the 95 percent confidence interval of the best-fit estimate.

Source: Lawrence Berkeley National Laboratory

Results from the transient model are shown in Figure 39 and Figure 40. The transient model resulted in Q estimates that, when used to predict indoor CO_2 concentrations, resulted in predictions that agreed well with measurements for office space 1. Table 20 shows that the predicted VR for office space 1 has a mean value of 1.7/h, which is very close to the value measured using decay test (1.6/h). However, there was considerable variability from day to day (1.0/h to 2.2/h). This means that to use the transient method to estimate VRs, multiday measurements of CO_2 and people counts should be gathered to improve accuracy of the estimates.

Table 20 shows that for office space 1, the steady-state method also gave a VR (mean = 1.9/h) that is relatively close to the measured value from decay test (1.6/h). However, these results were obtained using a CO_2 generation rate that required knowing the maximum 1-hour average occupant counts, which varied from day to day (range = 30 to 62, mean = 47). Without the IR camera, it would be difficult to estimate the maximum 1-hour average occupants in office space 1. If the assumed occupant counts of 98 (i.e. 73 office workers + 25 occupants in conference rooms, assuming half capacity) were used instead, the steady-state method would greatly overestimate the VR (mean = 4.0/h).

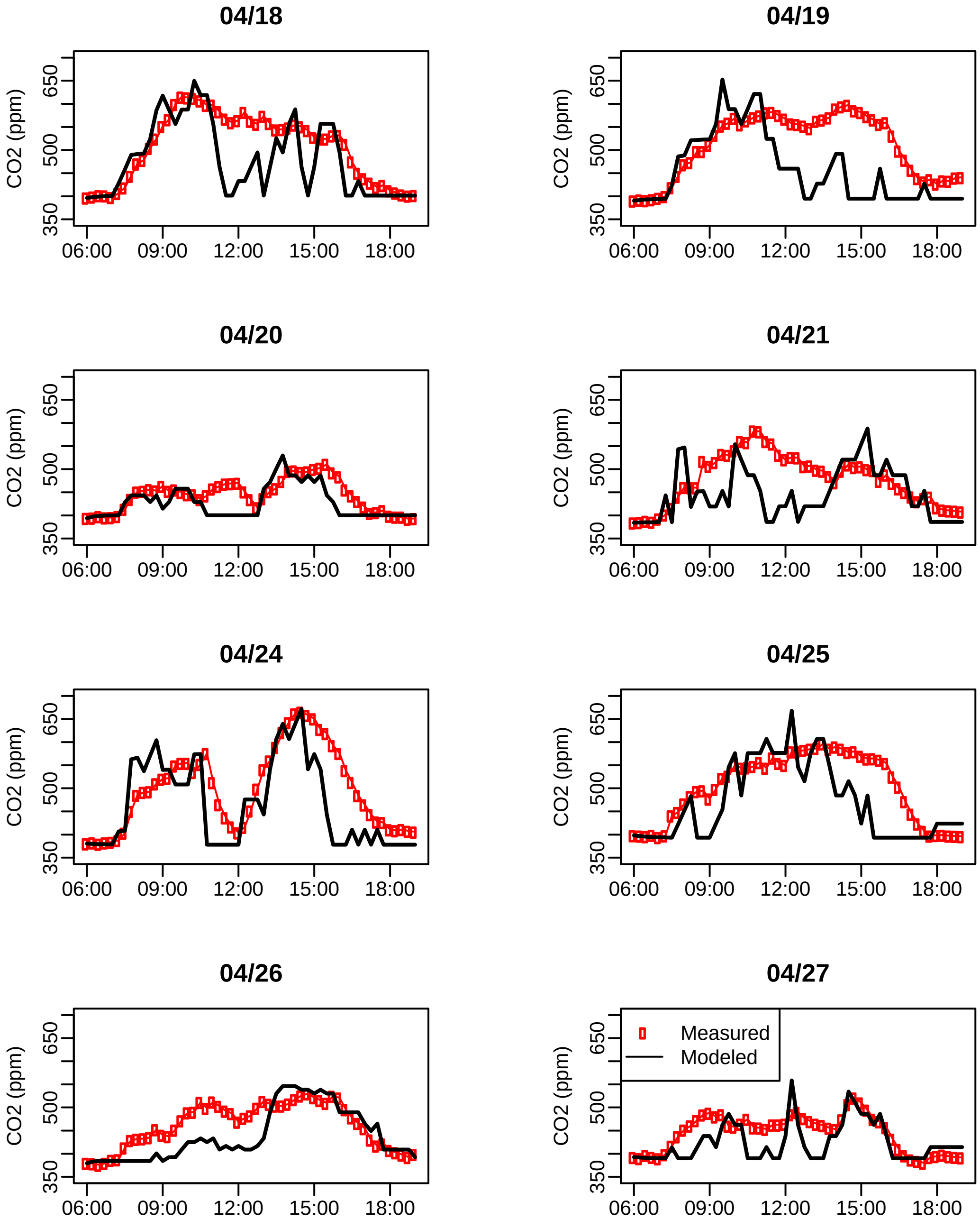
Figure 39: Comparison of Measured and Modeled Carbon Dioxide for Office Test Space 1



Using ventilation rates estimated from transient model

Source: Lawrence Berkeley National Laboratory

Figure 40: Comparison of Measured and Modeled Carbon Dioxide for Office Test Space 2

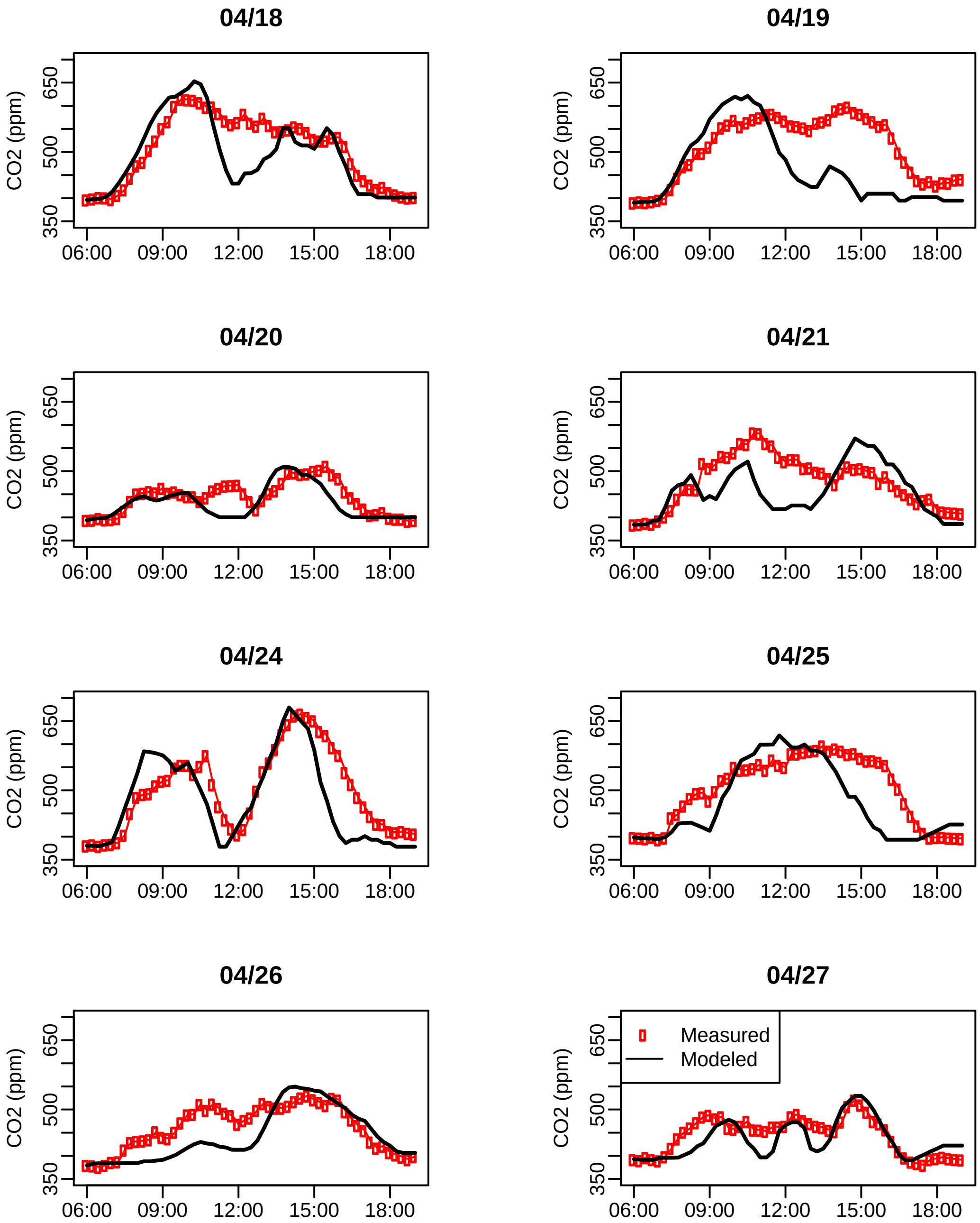


Using ventilation rates estimated from transient model.

Source: Lawrence Berkeley National Laboratory

The transient method also gave a reasonable central estimate of VR = 1.8/h for office space 2. However, Figure 40 shows that in a small office space where occupant counts obtained from IR camera were more uncertain, the predicted indoor CO_2 using Q estimated from the transient method agreed less well with measured data. For example, if the 15-minute people counts used in the transient model were smoothed using a running average of five consecutive values (e.g., N at 9 am is estimated by taking an average of values at 8:30, 8:45, 9:00, 9:15, and 9:30), the modeled CO_2 concentration would agree more closely with measured values (Figure 41). These modified results gave an estimate of VR of 1.6/h (range = 0.9/h to 4.5/h).

Figure 41: Modified Modeled Results using 1-Hour Averaged People Counts Measured at Office Test Space 2



Source: Lawrence Berkeley National Laboratory

Table 20: Ventilation Rates Estimated Using Transient and Steady-State Methods for Office Test Space 1

Date	Transient Model Q/V (1/h)	Model Fit R^2	C_{out} (ppm)	C_{max} (ppm)	N_{max}	Steady State Q/V (1/h)
3/27	1.5	0.86	413	543	40	1.7
3/28	2.0	0.94	415	538	48	2.2
3/29	1.9	0.93	417	592	62	2.0
3/30	1.5	0.77	420	528	31	1.6
3/31	2.1	0.96	413	525	44	2.2
4/3	1.6	0.87	415	536	42	1.9
4/4	2.2	0.97	418	559	60	2.4
4/5	1.5	0.89	414	579	52	1.7
4/6	1.6	0.92	412	582	58	1.9
4/7	1.0	0.84	408	562	30	1.1
Mean	1.7	0.89	414	554	47	1.9
Range	1.0–2.2	0.77–0.97	408–420	525–592	30–62	1.1–2.4

Source: Lawrence Berkeley National Laboratory

Table 21: Ventilation Rates Estimated Using Transient and Steady-State Methods for Office Test Space 2

Date	Transient Model Q/V (1/h)	Model Fit R^2	C_{out} (ppm)	C_{max} (ppm)	N_{max}	Steady State Q/V (1/h)
3/27	1.2	0.46	401	620	7	1.2
3/28	1.1	0.21	395	598	6	1.2
3/29	2.6	0.39	400	514	7	2.3
3/30	1.1	0.16	386	593	5	0.9
3/31	1.1	0.47	378	667	8	1.0
4/3	1.2	0.47	393	601	7	1.2
4/4	4.7	0.52	384	532	20	5.1
4/5	1.6	0.38	390	522	5	1.4
Mean	1.8	0.38	391	581	8	1.8
Range	1.1–4.7	0.16–0.52	378–401	514–667	5–20	0.9–5.1

Source: Lawrence Berkeley National Laboratory

Office space 2 only had on average 8 occupants during the monitoring period. If the default value of 15 occupants was used instead, the steady state method would give an estimate VR of 3.2/h (range = 2.0/h to 5.0/h).

Discussion

The steady-state method, if applied using the peak CO_2 concentrations measured, will likely overestimate VR if the default occupant count is used. This is because occupant counts in office spaces are often less than the default values, since some fraction of office workers may be traveling for work, on vacation, or working from home. For the two office spaces studied, the transient method estimated a VR that agrees well with the measured value using decay test. The steady-state method also gave a reasonable estimate of VR, if the actual peak occupancy is used for the calculation.

Adjustments of the IR camera were needed so that occupant counts do not become negative, and counting error is not propagated from one day to another. The simple approach here may not be suitable in all cases (for example, occupant counts in buildings that are occupied 24/7 could not be easily reset to zero each night). The research team found that the proper setup and checking of the people counting system with manual observation is important but time consuming.

As illustrated by the difference in performance comparing the two office spaces studied, there are specific challenges that were encountered during the installation process. For example, office space 1 has a set of west-facing windows with direct sunlight that were found to cause counting errors by the IR camera. Counting errors from IR camera in the smaller office space 2 resulted in occupant counts that deviated more from manual observations. The research team observed occupants in the small office space often congregate near the doorway, resulting in counting errors from the IR camera. This study only tested one type of people counters. Other site-specific challenges will need to be overcome to obtain reliable data when applying these technologies.

This study compared VRs estimated using transient model and steady-state method with values determined from CO_2 decay tests that were conducted on separate days. Even though steps were taken to ensure that VRs during the decay tests were representative for the respective study spaces, day-to-day differences in VRs may result from different weather conditions, occupant behaviors (for example, open windows). Concurrent measurements of VRs during monitoring of CO_2 and people counts would be needed to eliminate this uncertainty.

Batterman (2017) found that for determining classroom VRs, the transient model provided the most consistent and accurate results among the different CO_2-based methods evaluated. In two office settings, however, this study found that the transient model and steady-state method gave similar results, as long as the actual peak occupancy was used when calculating VRs using the steady-state assumption. The advantage of using the transient model is likely more evident in classrooms because of variable occupancy patterns.

Conclusions

A transient mass balance model was applied to calculate VRs using CO_2 concentration and people counts measured in two office spaces for two weeks each. The accuracy of the estimated VR using this transient method was determined by comparing with VR measured using a tracer gas decay as the reference. In addition, VRs were also computed using steady state method, where peak CO_2 and peak occupancy measured were used in the calculation of VRs.

Ventilation rates determined using the transient model agreed with the reference value on average. However, there was substantial day-to-day variability in the estimated VRs. This suggests that multiday CO_2 and occupancy data are needed to accurately estimate the VR using the transient model.

In the office setting, VRs calculated using the steady-state assumption and actual occupancy also agreed with the reference value on average. However, other types of buildings (e.g., classrooms) may have more variable occupancy patterns where the steady-state method may not apply.

The research team found site-specific challenges of using the IR camera to determine people counts. Counting errors were found to be more influential in small spaces with low occupant counts, when the data was used to calculate VRs. Site-specific guidelines are needed to help users of people counting technologies to ensure that the system is giving accurate data, if the data is used to measure and/or control VRs.

CHAPTER 4: Practical Guidance for Implementation

The research team developed occupancy-specific guidelines for using CO_2 sensors in DCV systems and for measurement of VRs using results from this project and other available data. Topics covered include: CO_2 sensor selection, calibration, and required accuracy; CO_2 sensor placement and density; and selection and use of technologies for measuring OA intake rates.

This information is also being shared with the public on ventcon.lbl.gov. The website also provides background information on the importance of ventilation and the energy savings potential of DCV.

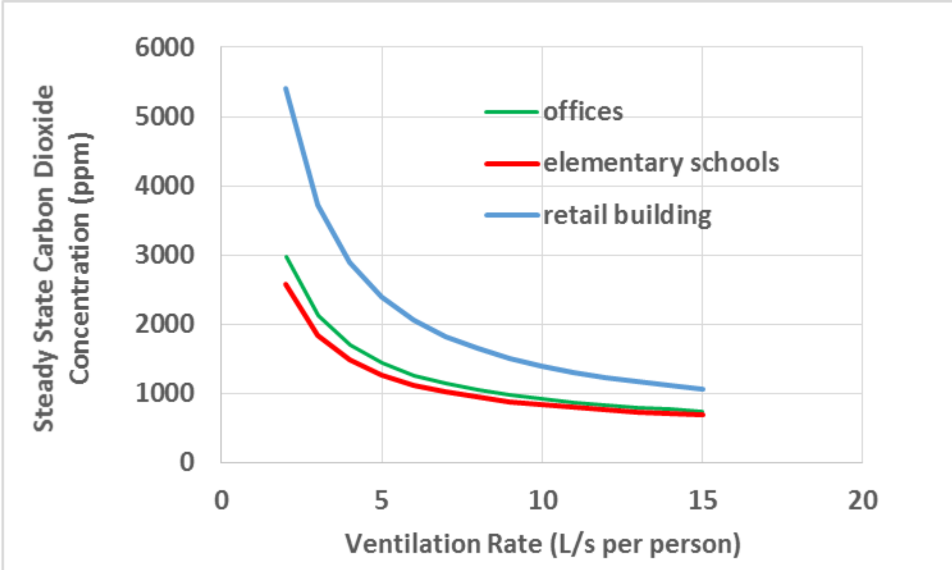
Carbon Dioxide Sensors for Demand-Controlled Ventilation

California's Title 24 Building Energy Efficiency Standards, as of 2016, require DCV systems for many spaces with a high and variable occupant density. DCV is sometimes used in other space types even when not required by codes. DCV systems use CO_2 sensors in the occupied space that send a signal to the ventilation control system. For single-zone systems, the control system modulates the rate of outdoor air supply, when the economizer is not activated, to maintain the indoor CO_2 concentration near a set point which is usually 1,000 ppm or 600 ppm above an assumed outdoor air CO_2 concentration of 400 ppm.

The main purpose of DCV is to save energy by allowing reduced ventilation when actual occupancy is less than design occupancy. Title 24 requires provision of a minimum rate of outdoor air supply per unit of floor area during occupancy, regardless of the indoor CO_2 concentration. Multizone variable air volume systems will often first increase the airflow rate at the spaces that have DCV, then increase the outdoor air intake rate at the air handler to meet demand. (See ASHRAE Guideline 36—High Performance Sequences of Operation for HVAC Systems—for more detailed discussions on different DCV implementation approaches.)

Figure 42 shows estimates of the steady-state relationships of indoor CO_2 concentrations and VRs per person provided in three building types, based on published CO_2 generation rates for offices (ASHRAE 2016), elementary schools, (Haverinen-Shaughnessy, Moschandreas et al. 2011), and retail buildings (Chan, Cohn et al. 2015). The relationship varies among space types because CO_2 generation rates per person vary as a function of occupant features (for example, weight) and activity levels. The figure was produced assuming an outdoor concentration of 400 parts per million (ppm).

Figure 42: Estimated Steady-State Relationships Between Ventilation Rates and CO_2 Concentrations



Source: Lawrence Berkeley National Laboratory

Carbon Dioxide Sensor Selection

Title 24 specifies the following accuracy requirements for CO_2 sensors used for DCV:

> "CO_2 sensors shall be certified by the manufacturer to be accurate within plus or minus 75 ppm at a 600 and 1,000 ppm concentration when measured at sea level and 25°C, factory calibrated, and certified by the manufacturer to require calibration no more frequently than once every 5 years. Upon detection of sensor failure, the system shall provide a signal which resets to supply the minimum quantity of outside air to levels required by Section 120.1(b)2 to the zone serviced by the sensor at all times that the zone is occupied."

Nearly all CO_2 sensors marketed for DCV applications contain specifications certifying that they meet the requirements of Title 24. The available data, however, indicate that in practice CO_2 measurement accuracy can sometimes be much poorer than indicated by manufacturer's specifications (Fisk, Faulkner et al. 2009, Shrestha 2009). NBCIP (2010) found no specific CO_2 sensor design types are consistently superior in terms of accuracy when sensors were new. CO_2 sensor sensitivity to temperature and humidity is usually negligibly small, for sensors installed indoors, but there is a positive relationship between barometric pressure and CO_2 sensor response. For example, CO_2 sensor reading may change by 50 ppm at a reference concentration of 1,100 ppm, in response to a change in 0.5 pounds per square inch (3.5 kiloPascals) of barometric pressure.

The two-year evaluation of CO_2 sensor accuracy performed in three spaces (office, conference room, and classroom; see Figure 24) found errors in CO_2 measurements in the classroom exceeding ±75 ppm for a large fraction of the time. The agreement of

CO_2 sensors with the reference instrument was better overall in office and conference room. In an office and conference room, a single lamp single wavelength sensor design with auto-calibration agreed with reference instrument better than the dual channel model by the same manufacturer. But CO_2 sensor accuracy differed by manufacturer. Among the seven CO_2 sensors evaluated for accuracy, the two that best agreed with the reference instrument used different sensor designs (for example, one uses auto-calibration and the other does not).

Many of the CO_2 sensors available for DCV applications incorporate an auto-calibration system that periodically resets the sensor's calibration based on the lowest measured CO_2 concentration during a prior period, assuming that that lowest measured concentration is approximately 400 ppm—a typical outdoor CO_2 concentration. This auto-calibration procedure is sometimes referred to as an "automatic baseline adjustment" or "automatic background calibration". While this auto-calibration scheme is suitable for many spaces, sensors with this scheme are not suitable for spaces with indoor CO_2 concentrations consistently maintained above the outdoor concentration, such as buildings with continuous occupancy. Also, concentrations of CO_2 in some classrooms can stay above 400 ppm overnight throughout a school week, although concentrations may still fall below 400 ppm on weekends.

When selecting CO_2 sensors for DCV, the maximum measurable concentration of the sensor is another consideration. Many available products can measure CO_2 concentrations up to 2,000 ppm or 5,000 ppm. In general, accuracy will be improved if the maximum measurable concentration of the sensor is not far above the maximum concentration encountered in practice. For example, if the CO_2 sensor is to be used to maintain CO_2 concentrations below 1,000 ppm, a sensor with a maximum measurable concentration of 2,000 ppm will usually be preferable to a sensor with a maximum measurable concentration of 5,000 ppm.

Carbon Dioxide Sensor Calibration

Given current knowledge on CO_2 sensor accuracy, it is recommended that sensors be calibrated shortly after installation, and periodically thereafter. The calibration process exposes the sensor to one or more accurately known CO_2 concentrations using one or more calibration gas mixtures. The sensor's zero and or gain parameters are then adjusted so that the sensor accurately reports the concentrations of CO_2 in the calibration gases. CO_2 sensors that incorporate an auto-calibration system that periodically resets the sensor's calibration based on the lowest measured CO_2 concentration during a prior period should be deployed in the occupied space for approximately two weeks before an initial calibration check. During this initial period of deployment, the sensor's self-calibration system may be making rapid adjustments in the sensor's output.

Some of the CO_2 sensors sold for DCV applications have no provisions for convenient calibration in field settings. Other sensors can be provided with a port or apparatus for introducing a calibration gas and the manufacturer provides a calibration procedure and may market a calibration kit. Some calibration systems can be located by searching the web for "CO_2 sensor calibration kits". If the user plans on performing calibrations, which is recommended, they should select the second of these two types of CO_2 sensors and follow the manufacturers' calibration procedures. Because the output signal of CO_2 sensors is affected by air pressure, it is important to introduce a calibration gas in a manner that does not greatly change the air pressure in the sensor.

Even when direct calibration is not possible, the accuracy of installed CO_2 sensors can be checked using a calibrated portable reference CO_2 instrument. The reference instrument should be calibrated using calibration gas mixtures and then placed near the installed CO_2 sensor long enough to allow the instrument to stabilize, often less than one minute. The concentration of CO_2 indicated by the sensor can then be compared to the "true" concentration indicated by the reference instrument. In some cases, the manufacturer will provide a procedure for adjusting the calibration of the CO_2 sensor, if such a procedure is not available, a correction can be made using software. During this calibration check process, it is critical to avoid exhaling high CO_2 breath toward the CO_2 sensor and reference instrument. Quality portable CO_2 calibration instruments usually cost at least $1,000. Less expensive portable instruments might be usable for this application if their calibration is checked before and after the period of use and found to be stable.

Few data are available for development of recommended calibration intervals for CO_2 sensors. Calibration intervals recommended by manufacturers range from three years to never needed, with five years the most common. Sensor tests over a year found that many sensors had a change in output less than 75 ppm at a CO_2 concentration of 1,100 ppm (Shrestha 2009). Other sensors had a less stable calibration, with a maximum change in output of -376 ppm over one year.

The two-year evaluation of CO_2 sensor accuracy performed in three spaces (office, conference room, and classroom, see Figure 24) also found that changes in outputs varied among sensors. Some CO_2 sensors showed systematic changes in output of about 5 percent per year (i.e. 50 ppm at a reference concentration of 1,000 ppm). Other sensors showed no systemic changes in output over the same period.

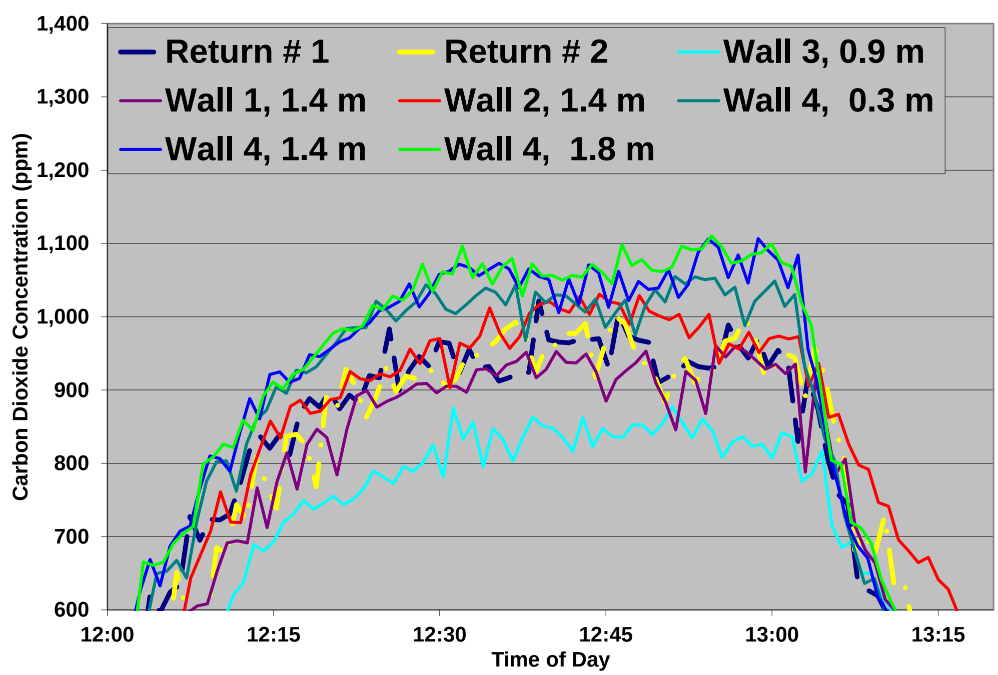
If neither a direct calibration nor a check with a reference instrument is possible, sometime faulty sensors can be detected via a simple examination of sensor output data. In an intermittently occupied space, a properly operating CO_2 sensor will report a concentration that decreases, usually to about 400 ppm, when the building has been unoccupied for many hours and will report a concentration that increases during occupancy. Also, sensors that indicate CO_2 concentrations very different from surrounding sensors should be checked for accuracy. Using sensors with a visual display of CO_2 concentration can facilitate identification of faulty sensors, such as by noting if CO_2 concentration changes in response to exhaled CO_2.

Carbon Dioxide Sensor Placement and Density

Where DCV is required, California's Title 24 requires "no less than one sensor per 10,000 ft² (930 m^2) of floor space". Title 24 also specifies that "CO_2 sensors shall be located in the room between 3 ft and 6 ft (0.9 m and 1.8 m) above the floor or at the anticipated height of the occupants' heads."

Very few empirical data are available for guidance on proper selection of CO_2 sensor installation locations. Multi-location and multi-height measurements of CO_2 concentrations in meeting rooms (Fisk , Mendell et al. 2012) indicated that concentrations of CO_2 at different wall-mounted sample points sometimes varied with location by more than 200 ppm. Figure 43 shows an example of the data from this study. This research indicated that measurements of CO_2 at return air grilles was a better choice than measurements with sensors located at walls, but measurements at return air grilles is not permitted in California's Title 24 to avoid the potential influence from recirculating supply air. The research found that the exhaled breath of occupants in a meeting room can cause large fluctuations in the output of nearby CO_2 sensors, thus, it is recommended that sensors be located away from locations where occupants are likely to sit or stand.

Figure 43: Example of Spatial Variability of Carbon Dioxide Concentrations in a Meeting Room



Source: Lawrence Berkeley National Laboratory

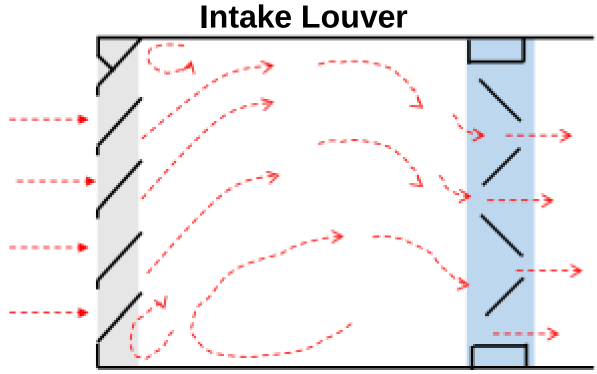
Technologies for Measuring Outdoor Air Intake Rates

Several outdoor airflow measurement technologies (OAMT) are marketed to meet the need for better measurement and control of outdoor air VRs in commercial buildings. The designs of commercially available OAMT system are highly variable. Some systems consist of electronic velocity probes with multiple sensors that are installed, as specified by the manufacturer, downstream of an outdoor air intake louver or inside an outdoor air intake hood. One OAMT consists of an outdoor air intake louver with integrated air velocity probes installed at the outlet of louver blades. Another system measures the pressure drop as air flows through a louver. One system uses air speed probes installed on the outdoor air damper and tracks the damper position. Most OAMTs are marketed as products that the user adds to their air handling unit but some are provided only as an optional component of a packaged heating, ventilating, and air conditioning system.

Measurement Challenges

Typically, the outdoor air enters an air handling unit through a louver or air intake hood which are present to limit the rates at which moisture (for example, rain) enters the air handler. Figure 44 shows a schematic of common outdoor air intake with a louver (gray) on the left through which outdoor enters and an outdoor air damper (blue) located downstream on the right. The red arrows illustrate an example of the resulting airflow pattern. Often, recirculated indoor air mixes with the outdoor air just downstream of the outdoor air damper; thus, the OAMT must be placed upstream of damper in the region with a complex airflow pattern. It is difficult to accurately measure the airflow rate through an airflow passage if the airflow is not parallel to the perimeter of that passage. Accurate measurements are also complicated by highly non-uniform air speeds. Additionally, louver designs vary and the downstream airflow patterns will vary with the design of the louver, posing measurement challenges that vary with the type of louver used.

Figure 44: Illustration of Airflow Pattern into an Air Handling System with an Air Intake Louver



Source: Lawrence Berkeley National Laboratory

Outdoor air intake hoods that are often used with packaged rooftop HVAC systems pose similar challenges. Intake hoods serve the same function as louvers, they limit moisture entry into the air handler. Different hood geometries can also force changes in airflow direction which, in-turn, lead to complex airflow profiles and uneven air speeds.

The ASHRAE minimum ventilation standard (ASHRAE 2016) specifies that air speeds in an intake hood should not exceed 2.5 m/s (500 fpm). If the air handler has an economizer, air speeds when minimum outside air is supplied will be much lower, often 80 percent lower, resulting in air speeds of 0.5 m/s (100 fpm). Accurate measurement of these low air speeds is challenging. At 0.5 m/s (100 fpm), the velocity pressure is only 0.15 Pa (0.006 inches of water) which is too small for accurate measurement with the pressure transducers used with air handling systems.

Recommendations

Test results described in this report, and prior evaluations of OAMTs, indicate large measurement errors under some situations. These results indicate the importance of further development of OAMTs. Available data suggest the following keys to accurate measurements, at least when winds speeds are low:

- Condition the airflow so that the direction of flow is controlled and the air speed is as uniform as possible at the air speed sensors.
- Make sure that the sensors used can accurately measure the low airspeeds encountered in outdoor air intakes when minimum rates of outdoor airflow are provided.
- Employ a damper system to increase air speeds at the sensors when minimum rates of outdoor air supply are provided.

A prior development and evaluation of new prototype OAMTs indicate better accuracy when OAMT designs employ these principles (Fisk, Faulkner et al. 2005a, Fisk, Faulkner et al. 2005b, Fisk, Faulkner et al. 2005c).

One option for today's practice may be to develop installation-specific calibration factors that can be used to correct OAMT output signals under some operating conditions, and to be warned of measurements made when wind speeds are high. However, it is not clear that standard air balance tools and practices will yield sufficiently accurate determinations of true outdoor intake airflows and sufficiently accurate calibration factors. No evaluations of this option are available.

A second option is to use dampers to produce separate outdoor air intake systems for minimum outdoor air flows and the increased airflows when economizers are activated, and to then use OAMTs to only measure rates of minimum outdoor air supply. This practice enables much higher airspeeds to be maintained at the sensors of the OAMT during minimum outdoor air supply and the higher velocities should also reduce the effects of wind on accuracy. One of the OAMTs evaluated previously (Fisk, Faulkner et al. 2005a), that integrates velocity probes together with a vertical blade louver, maintained high accuracy when velocities were sufficiently high and could be used in such a system. A new prototype OAMTs also successfully used this approach (Fisk, Chan et al. 2015). However, these prototypes are not available commercially. Some practitioners have developed calibration coefficients to relate the outdoor airflow with the pressure drop across the damper for the minimum outdoor airflow, although no formal assessment of this type of system was identified.

CHAPTER 5: Findings and Recommendations

Outdoor air VRs in commercial buildings are important because they influence building energy use and occupant health and performance. Prior research indicates that MVRs in commercial buildings are often poorly controlled. MVRs in office and retail buildings often far exceed the requirements specified in California's Title 24 Standards while VRs in schools are often far less than specified in Title 24 standards.

This research project has advanced the related understanding of the benefits of, and technologies for, better measurement and control of VRs in commercial buildings. Key findings include:

- Modeling for various buildings types in each California climate zone has improved the understanding of the potential energy savings of different strategies for DCV and indicate how these DCV strategies will affect indoor air quality. On average, the potential HVAC energy savings are substantial, about 10 percent, when properly performing DCV systems are employed in California's commercial buildings with high occupant density. The energy savings potential differed little among the control strategies. The findings indicate that, in schools, DCV could considerably improve indoor air quality with only minor impacts on energy consumption. The modeling indicated the potential of a novel DCV control strategy that does not require CO_2 sensors or people counters. This DCV strategy employs a model to indicate when MVRs can be reduced because of prior periods of economizer operation that have driven down indoor air pollutant concentrations.
- The project included evaluations of two commercially available outdoor airflow measurement technologies (OAMTs), which measure the rates of outdoor air intake into HVAC systems. The data obtained and data from prior research indicate a potential for large errors in the reported rates of outdoor air intake under common installation and operating conditions. The research shows how the type of upstream louver or air intake hood affect accuracy and how wind speeds and direction can affect accuracy. The research results can improve decisions about the selection and use of OAMTs, but the research did not identify widely practical means of deploying OAMTs, and obtaining accurate data, without installation specific calibrations.
- The project's evaluation of several types of CO_2 sensors over time indicates improvements in CO_2 measurement accuracy relative to prior studies of older sensor technologies. However, based on the newest data, sensor calibrations, at the time of initial sensor installation and periodically thereafter, are still recommended. The data obtained in this project will help building designers and operators make better decisions about CO_2 sensor selection and use.

- The project evaluated two people counting technologies potentially suitable for use with DCV systems. Under most conditions, the people counters had a sufficient accuracy for DCV. The research results indicate how the preferred people counting technology type will vary with the application.
- The final technical task of the project included preliminary evaluation of a new concept for measuring VRs in commercial buildings. Data on people counts and CO_2 concentrations were used in a transient CO_2 concentration model to estimate VRs. If this measurement approach was sufficiently accurate, it could be used to determine if VRs comply with requirements in standards or otherwise meet design goals. The preliminary evaluation suggests that the average of multiple measurements with this approach indicate approximately the correct VR; however, measurement precision was not sufficiently high to enable reliance on a single measurement.

The results of this research also suggest a need for further research and product development pertaining to measurement and control of VRs in commercial buildings, as well as suggest some changes in practice. Examples are described in the following paragraphs.

- The results of modeling of DCV options indicate the large potential benefits of applying DCV in general office spaces and stores with a high occupant density, and in schools. At present, California's Title 24 Standard does not necessarily require DCV in such spaces.
- The evaluations of OAMT indicate a need for development of new OAMTs that do not require installation-specific calibrations or a need for data, probably provided by manufacturers, that indicate OAMT calibration factors as a function of the type of upstream louver or air intake hood. The alternative is to require Testing, Adjusting and Balancing (TAB) for all OAMTs installation to ensure reliable performance; however, the accuracy of TAB data has not been well established.
- Further improvements on the accuracy of OAMT to reliably measure airflow rates, especially at low airflow rates when minimum VRs are provided.
- Testing results of current CO_2 sensor technologies, while indicating improvements in accuracy, suggest that field checks are still needed to identify faulty sensors. Practical CO_2 sensor fault detection tools or services are needed. Due to the difficulty of field-based calibrations, there is an opportunity for third parties to address this need. For example, a building owner would receive recently calibrated sensors to replace sensors needing calibration, which are then shipped to a third party for calibration and reuse.
- More research is recommended to evaluate the accuracy of people counting technologies potentially suitable for DCV applications, although questions on implementation remain as this technology is fundamentally different from CO_2-based method. Initial findings from scripted and in-situ tests are encouraging. In particular, accuracy over time needs to be assessed. If found sufficiently

accurate over time, changes in Title 24 standards could facilitate use of these technologies.

- Finally, more research is recommended to evaluate the accuracy of VR measurements using data on both people counts and CO2 concentrations together with transient CO2 concentration models. The limited evaluation included in this research project was insufficient for conclusions about the utility of this measurement approach.

LIST OF ACRONYMS

Term	Definition
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
cfm	Cubic feet per minute
CO_2 sensors	Carbon dioxide transmitters used in demand-controlled ventilation
CZ	Climate zone
DCV	Demand-controlled ventilation
EAMS	Electronic air measuring station
fpm	Feet per minute
HVAC	Heating, ventilation, and air conditioning
IOU	Investor owned utilities
IR	Infrared
kPa	Kilopascal
LBNL	Lawrence Berkeley National Laboratory
mm Hg	Millimeter of mercury
MVR	Minimum ventilation rate
OAMTs	Outdoor airflow measurement technologies
ppm	Parts per million
R Statistical Software	R is a free software for statistical computing and graphics: https://www.r-project.org/
Title 24	California's Title 24 are Building Energy Efficiency Standards for Residential and Nonresidential Buildings.
VFD	Variable frequency drive that controls HVAC fan speed
VR	Ventilation rate

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APPENDIX A: EnergyPlus Modeling of Demand-Controlled Ventilation

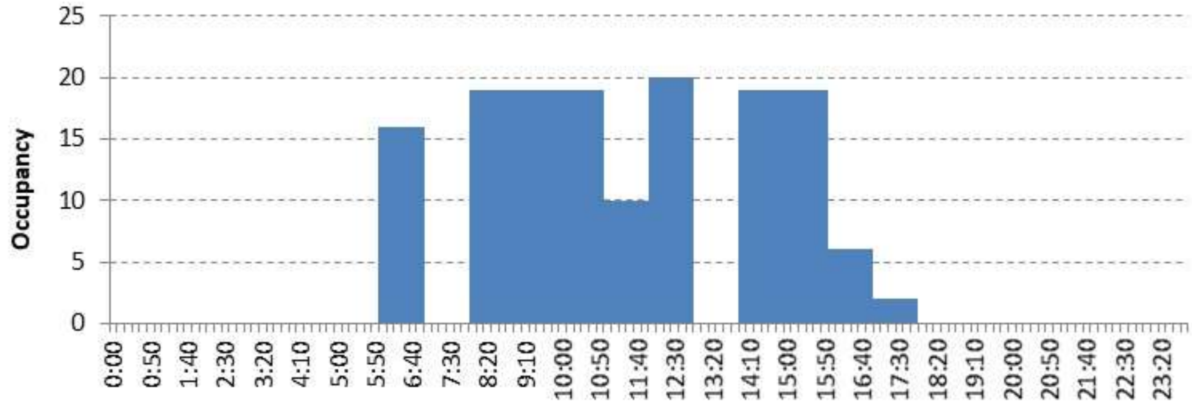
An initial verification was performed to ensure that EnergyPlus was able to accurately represent the control strategies covered in this study. EnergyPlus model outputs were checked using simple mass balance models. The purpose of the verification step was firstly, given a known set of inputs, ensure that the EnergyPlus models provided mass flows of ventilation air consistent with the intent; and secondly, to ensure that the DCV strategies that are the focus of this study can be reasonably modeled using EnergyPlus. For this series of tests, the small office model was used due to its simplicity and relatively quick simulation time.

A simple mass balance calculation in excel was used to confirm that the VRs predicted by EnergyPlus were consistent with the MVR requirement used as input. The building was first simulated using a square-form occupancy schedule without any variation during the period of occupancy, followed by a more detailed scenario with an occupancy schedule that includes periods of reduced and zero occupancy. Neither scenario is representative of "typical" office controls; they are intended for verification of modeled mass flow.

The initial verification test modeled the small office as fully occupied all weekdays and Saturday from 7 am to 7 pm. An assumed occupant density of 18.58 m^2/per person was used (peak occupancy of 20 people in an occupied area of 372 m^2). The building model was simulated with the economizer deactivated.

The second occupancy schedule had intermittent occupancy and periods of partial occupancy (Figure A-1). In this variable occupancy scenario, the prescribed MVR was specified to be the greater of either the per occupant rate, or ¼ of the prescribed per-floor-area MVR (Table A-1).

Figure A-1: Intermittent Occupancy Modeled for Verification of EnergyPlus Output



Source: Lawrence Berkeley National Laboratory

Table A-1: Occupant-Based Minimum Ventilation Rates Modeled for Verification of EnergyPlus Output

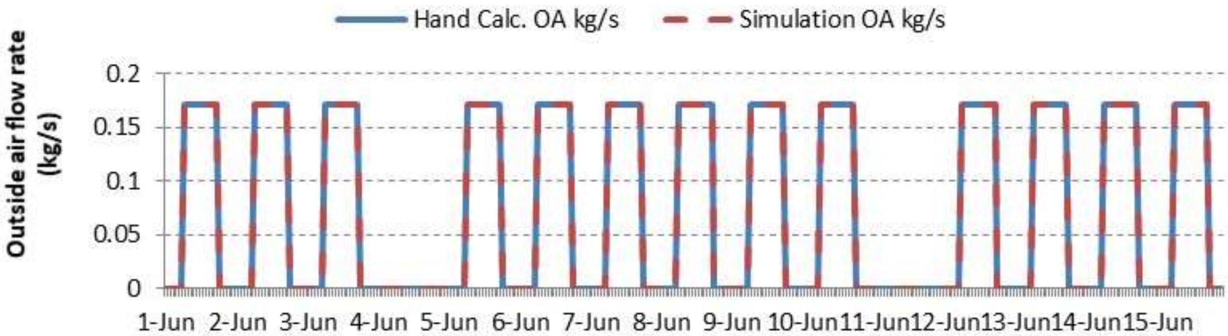
Period	Occupant-based MVRs
Unoccupied Period	0.00019 $m^3/s-m^2$ (0.15/4 CFM/ft^2)
Occupied Period	0.00708 m^3/s-person (15 CFM/person)

Source: Lawrence Berkeley National Laboratory

The intermittent occupancy scenario was intended to verify that MVRs consistently meet expected values even when the MVR control transitions between the per-person MVR and per-floor-area MVR. This scenario necessitates that the test building include an economizer, to modulate the VR. We forced the economizer system to only provide the MVR regardless of outdoor air temperature. For the purposes of the test, in the economizer control the researchers specified a maximum outside air temperature of 12°C, effectively eliminating periods of free cooling.

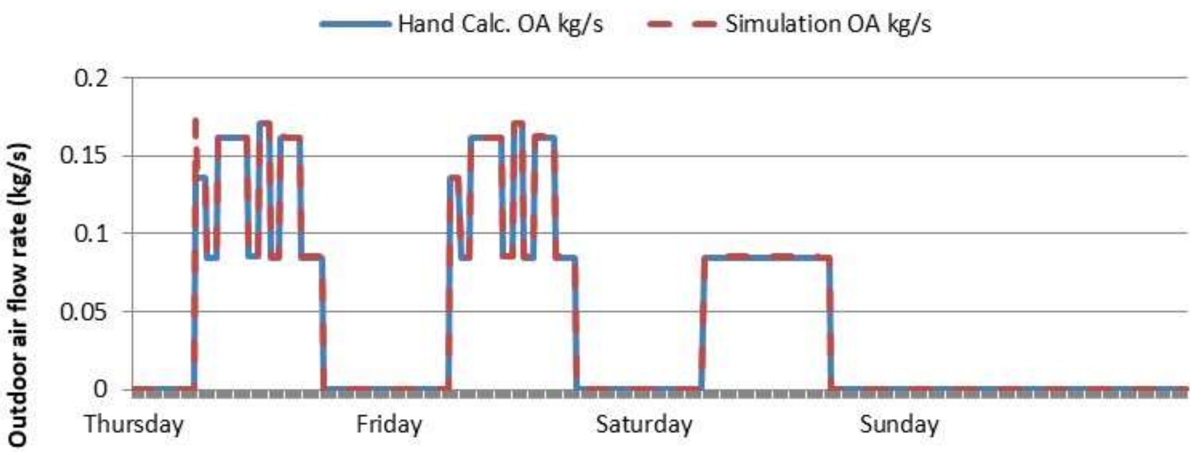
The initial verification results focus on demonstrating that the EnergyPlus models deliver the specified MVR, during periods when the economizer is deactivated. Results for a square-form occupancy schedule showed average daytime VRs were 0.171 kg/s. Using a simple occupancy based mass balance calculation performed using a spreadsheet, the VR was predicted to be 0.171 kg/s using a density of air of 1.2041 kg/m^3. A representative time series comparison is given in Figure A-2 for the fixed occupancy case, and Figure A-3 for the scenario with intermittent occupancy. The two figures compare outdoor air mass flow rates predicted by EnergyPlus and by a spreadsheet "hand" calculation as a check.

Figure A-2: Checking of Ventilation Rates Modeled with Fixed Occupancy



Source: Lawrence Berkeley National Laboratory

Figure A-3: Checking of Ventilation Rate Modeled with Intermittent Occupancy



Source: Lawrence Berkeley National Laboratory

The comparison with the hand calculation shows the model is performing as expected. MVRs are meeting the occupant-based requirement when that requirement exceeds the MVR required per unit floor area. A single time-step "blip" (Thursday 6am, Figure A-3) can be seen as the EnergyPlus simulation initially attempts to meet, but exceeds the target MVR. EnergyPlus' HVAC mass and energy balance calculation is solved iteratively, and these type of short term disparities with a simple steady state mass balance calculation are expected and are not expected to impact the outcome of this simulation study.

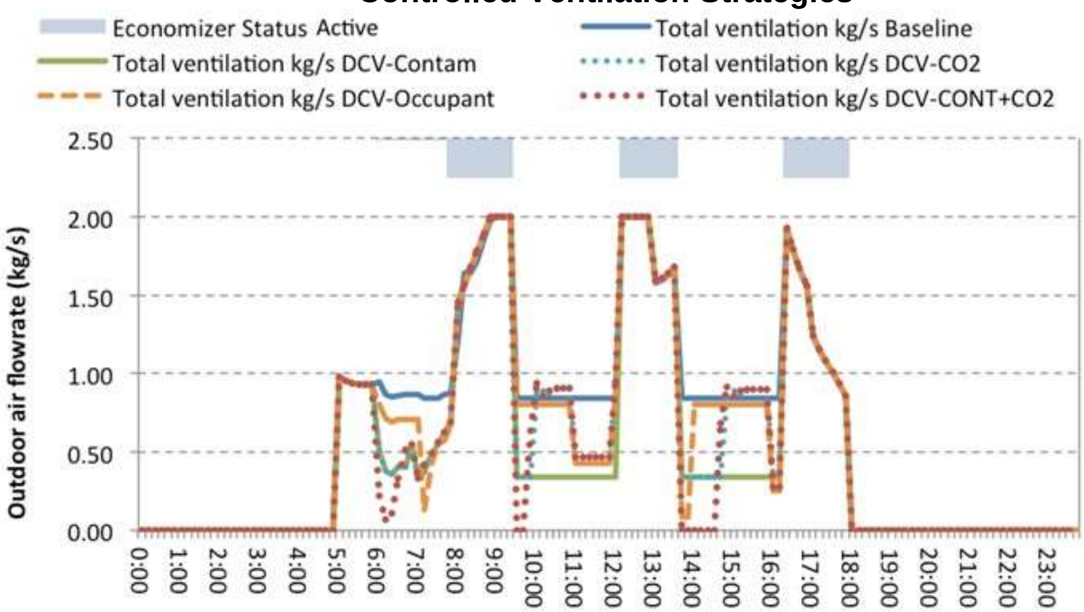
Demand-Controlled Ventilation Control Strategies

EnergyPlus model outputs were examined for the following different control strategies using the small office building as an example. The first control strategy, the baseline strategy incorporates no DCV, and serves as a reference. A first baseline assumes fixed MVRs as prescribed in Title 24. A second baseline assumes fixed MVRs consistent with measured data which, for schools and offices, differ from Title 24 MVRs. The four DCV strategies were: DCV based on capping the CO_2 concentration to below a threshold limit (DCV-CO_2); DCV based on occupant count (DCV-OCCUP); DCV based on limiting the indoor concentration of an indoor-generated continuously-emitted generic contaminant (DCV-CONT); and DCV based on limiting both indoor CO_2 concentrations and the indoor concentrations of the generic contaminant (DCV-CONT-CO_2).

For verifying correct operation of the DCV methods, occupant densities were increased to 3.7 m^2 per person. For each of the DCV methods, scenarios were developed to demonstrate the operation of the control system, for example, for the DCV strategy that controls VR based on the measured CO_2 concentration, a hot climate was used where the economizer would not normally have been active during the day, resulting in buildup of CO_2.

Figure A-4 gives the predicted MVR for four DCV scenarios and for the reference baseline scenario. On this particular example day, the economizer was operational during the morning, and during two periods in the afternoon. VRs can be seen to vary by control strategy; individual strategies are covered separately in more detail below.

Figure A-4: Ventilation Rate Comparison Modeled Using Different Demand-Controlled Ventilation Strategies

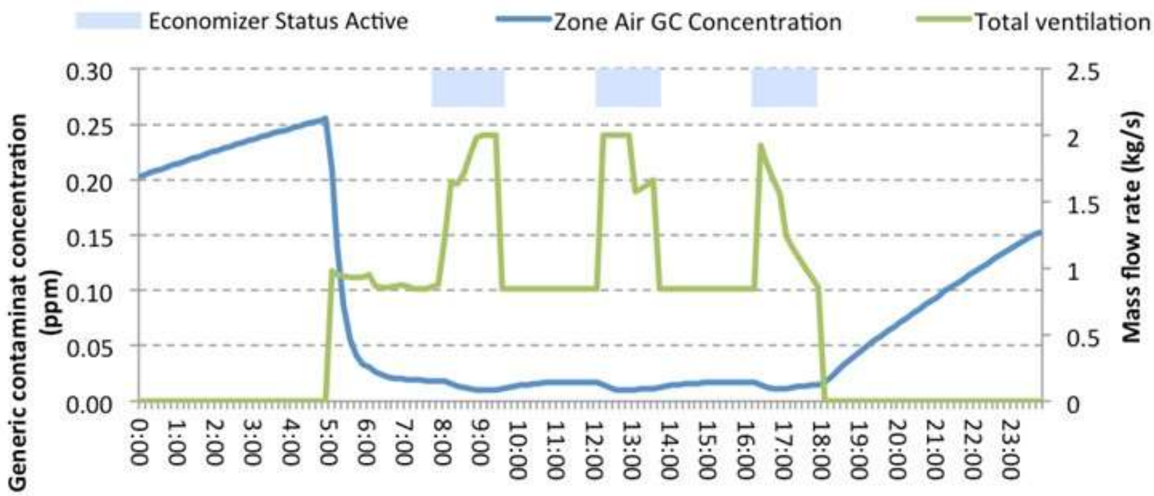


Source: Lawrence Berkeley National Laboratory

Baseline Scenario

Figure A-5 gives an example of the control behavior of the baseline control.

Figure A-5: EnergyPlus Baseline Model Outputs



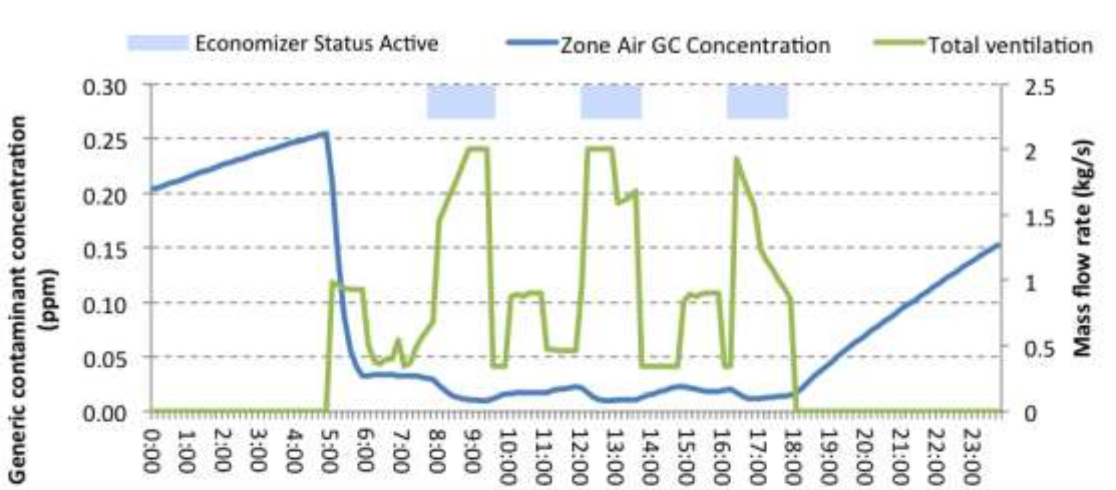
Source: Lawrence Berkeley National Laboratory

During periods when the economizer is deactivated, the MVRs are based on the peak occupancy of approximately 100 people. Results show the VR varying appreciably during periods when economizer is reported to be on. During the active economizer periods, the mass flow rate varies to meet the desired mixed air set point temperature. Between 5 am and 6 am, the system performs a purge to flush out contaminants before occupants arrive.

Demand-Controlled Ventilation Based on Carbon Dioxide

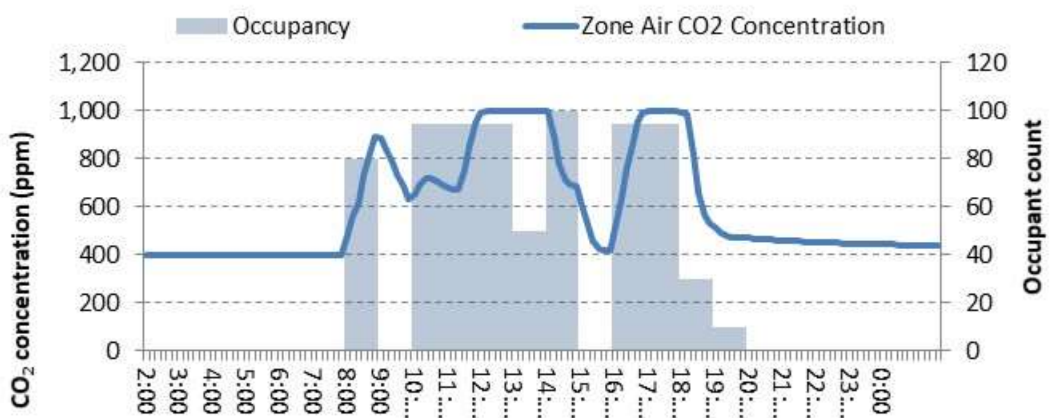
Figure A-6 shows VR modeled with DCV based on CO_2. By default even when CO_2 levels are below the limit, the control limits VR to always above per floor area rate. Figure A-7 shows that by providing required ventilation, DCV based on CO_2 prevents the CO_2 concentration from exceeding the 1,000 ppm threshold.

Figure A-6: Generic Contaminant Concentration and Ventilation Rate Modeled Using Carbon Dioxide Based Demand-Controlled Ventilation



Source: Lawrence Berkeley National Laboratory

Figure A-7: Occupancy and Modeled Carbon Dioxide Using Carbon Dioxide Based Demand-Controlled Ventilation

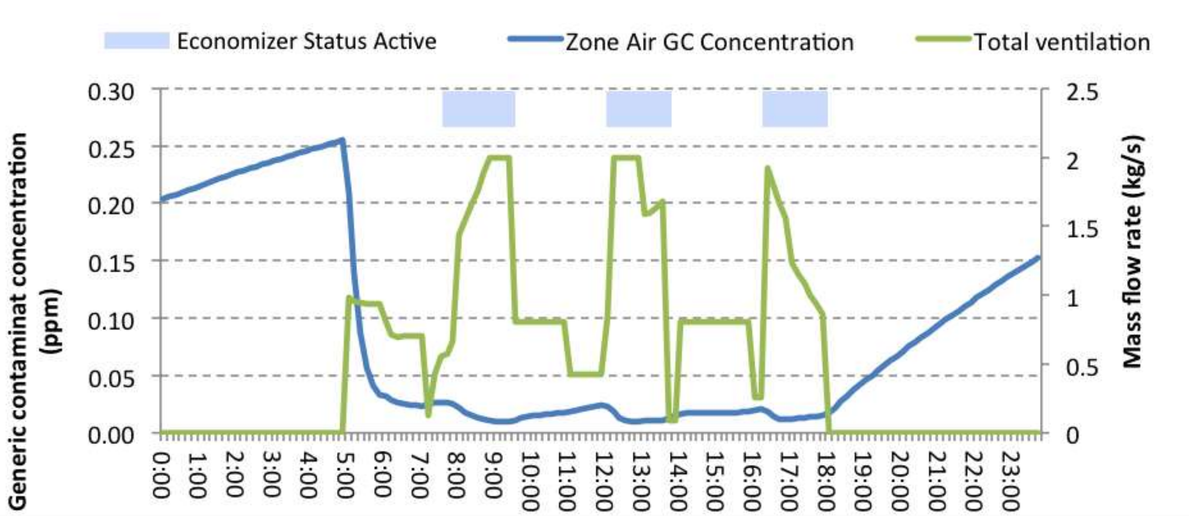


Source: Lawrence Berkeley National Laboratory

Demand-Controlled Ventilation Based on Occupant Count

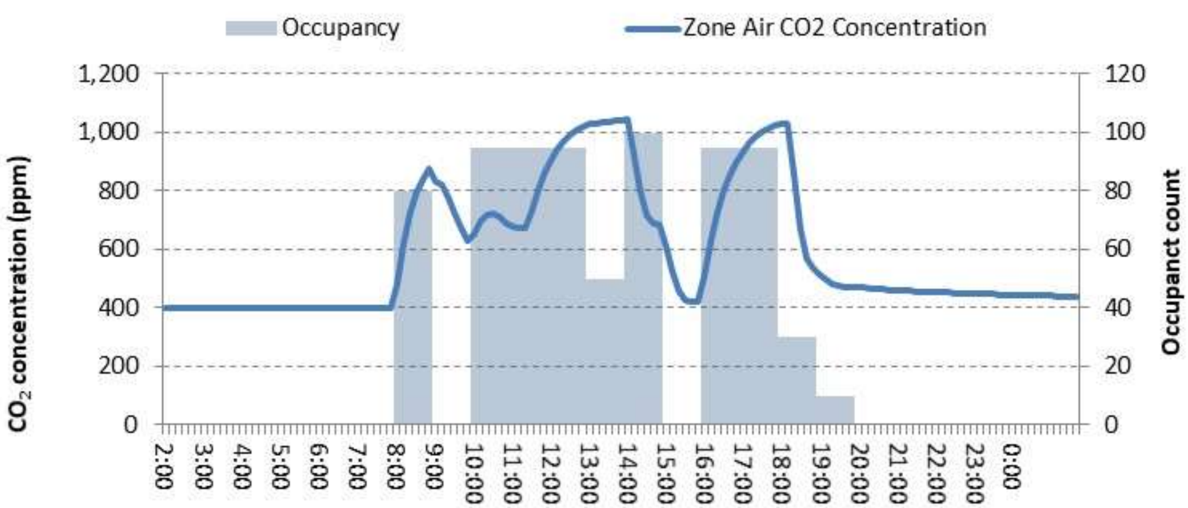
Figure A-8 shows that during periods of zero occupancy (9:00 to 10:00 and 15:00 to 16:00), the control lowers the MVR to the floor-area-based MVR. As seen in the earlier validation exercise, single time-step "blips" occur (note: there are 6 simulation time-steps per hour), where the VR falls below the per floor area rate. The impact this strategy has on the indoor concentrations of CO_2 can be seen in Figure A-9, with indoor concentrations of CO_2 briefly exceeding 1,000 ppm.

Figure A-8: Generic Contaminant Concentration and Ventilation Rate Modeled Using Demand-Controlled Ventilation Based on Occupant Count



Source: Lawrence Berkeley National Laboratory

Figure A-9: Occupancy and Modeled Carbon Dioxide for Demand-Controlled Ventilation Based on Occupant Count

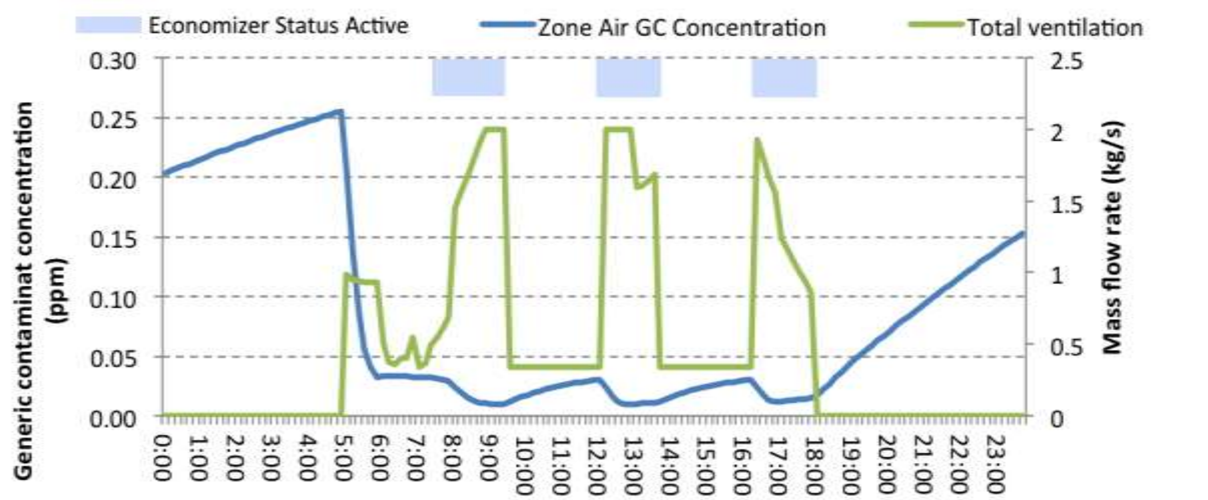


Source: Lawrence Berkeley National Laboratory

Demand-Controlled Ventilation Based on Generic Contaminant Level

Figure A-10 shows that for the day modeled, the economizer lowers the concentration of the generic contaminant to below the limit of 0.04 ppm, so the VR is at the per-floor-area MVR between periods of economizer operation.

Figure A-10: Generic Contaminant Concentration and Ventilation Rate Modeled Using Generic-Contaminant-Based Demand-Controlled Ventilation



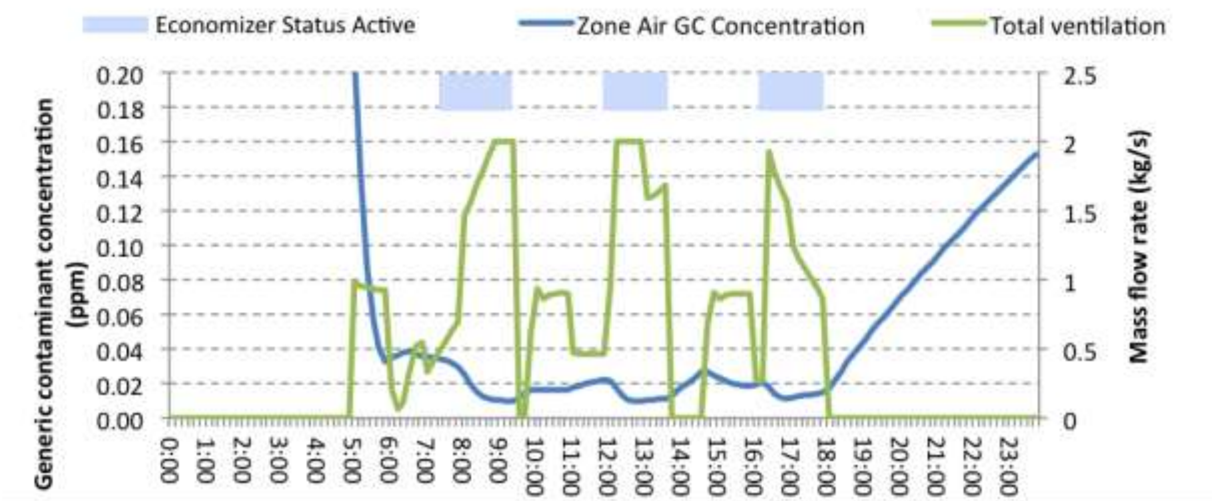
Source: Lawrence Berkeley National Laboratory

Demand-Controlled Ventilation Based on Carbon Dioxide and Generic Contaminant Level

The final DCV strategy combines the functionality of the previous two control strategies. First, the simulations were performed using the same generic contaminant emission rate used in the previous scenarios. However, as Figure A-11 shows, the generic contaminant threshold of 0.04 ppm is never actually reached because of increased VRs triggered by the CO_2 limit (Figure A-12).

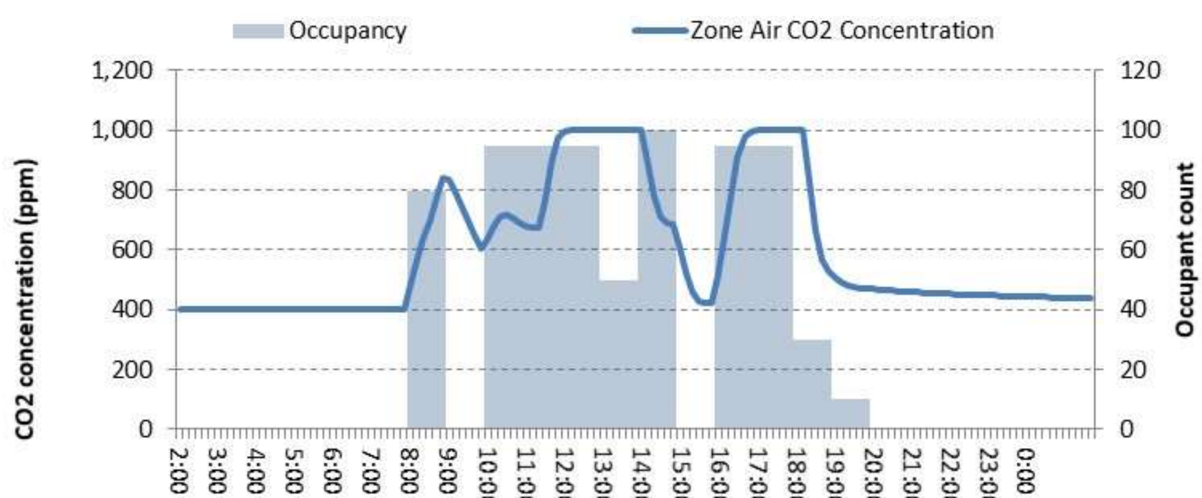
To see both control elements being active, a simulation scenario with a higher generic contaminant emission rate (x2.5) was modeled. In Figure A-13, the generic contaminant concentration can be seen to be driving the VR in some periods, as well as the CO_2 being a driver in other periods (Figure A-14).

Figure A-11: Generic Contaminant Concentration and Ventilation Rate Modeled Using Carbon Dioxide and Generic Contaminant Based Demand-Controlled Ventilation



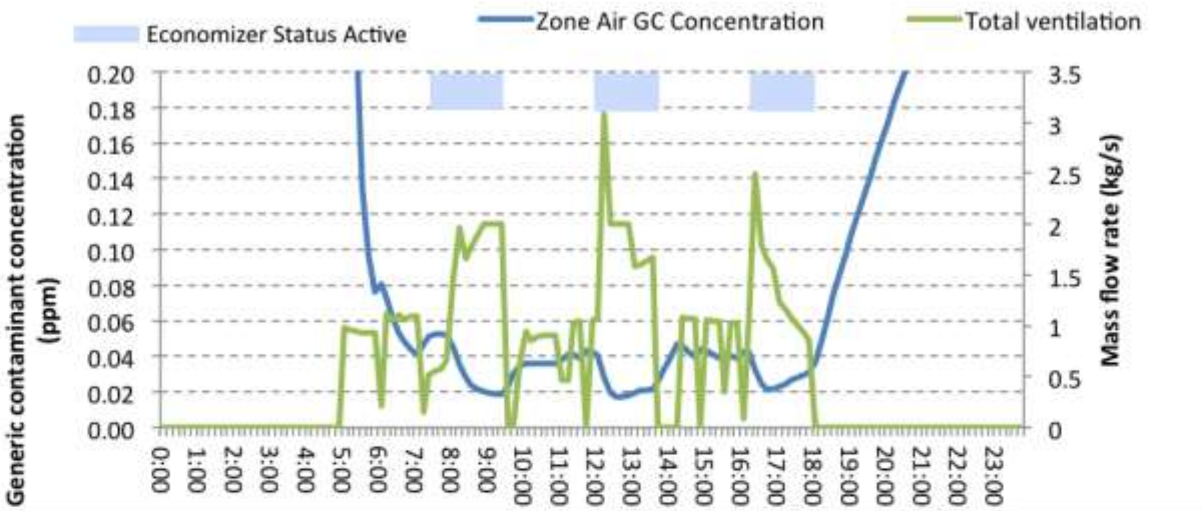
Source: Lawrence Berkeley National Laboratory

Figure A-12: Occupancy and Modeled Carbon Dioxide Using Carbon Dioxide and Generic Contaminant Based Demand-Controlled Ventilation



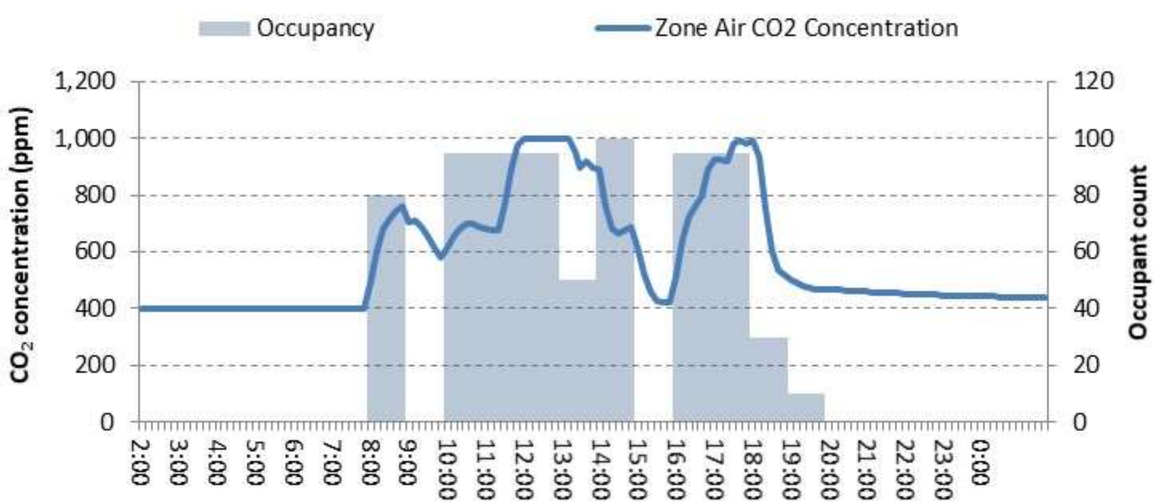
Source: Lawrence Berkeley National Laboratory

Figure A-13: Generic Contaminant Concentration and Ventilation Rate Modeled Using Carbon Dioxide and Generic Contaminant Based Demand-Controlled Ventilation, with Increased Generic Contaminant Emission Rate



Source: Lawrence Berkeley National Laboratory

Figure A-14: Occupancy and Carbon Dioxide Concentration Modeled Using Carbon Dioxide and Generic Contaminant Based Demand-Controlled Ventilation, with Increased Generic Contaminant Emission Rate



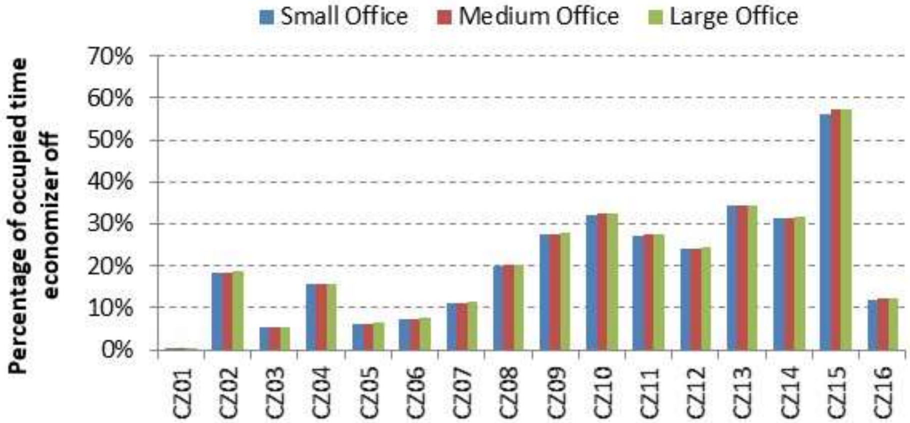
Source: Lawrence Berkeley National Laboratory

Economizer Use

DCV strategies are used to control VRs only when economizers are not active. As a result, it is important to understand the usage of economizer in California commercial buildings modeled.

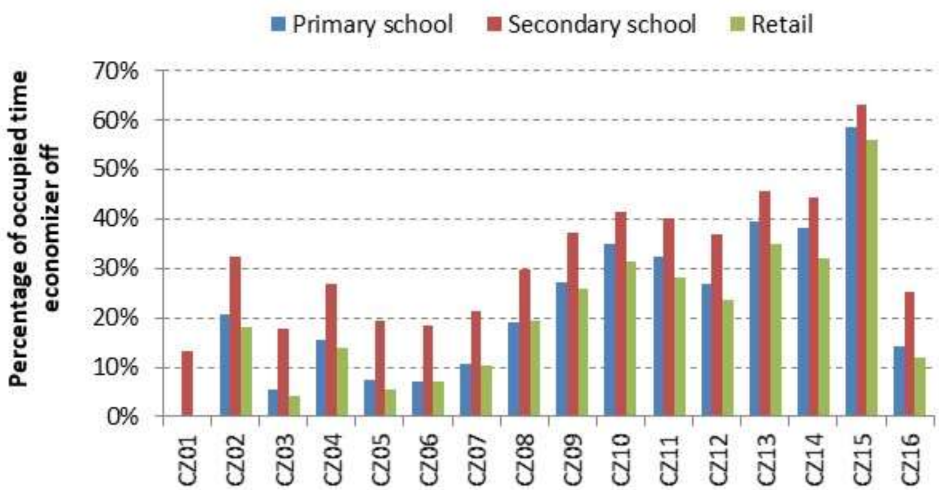
It is worth noting that the economizer use in schools was less than in the other building types. (Figure A-15 and Figure A-16). Economizer activation varied extensively with climate as expected.

Figure A-15: Average Percentage of Occupied Time When Economizer is Deactivated in Small, Medium, and Large Office, Modeled for 16 California Climate Zones



Source: Lawrence Berkeley National Laboratory

Figure A-16: Average Percentage of Occupied Time When Economizer is Deactivated in Schools and Retail Building, Modeled for 16 California Climate Zones



Source: Lawrence Berkeley National Laboratory

Figure A-17 shows statewide weighted average results for California. Results were not expected to differ notably between control strategies; this expectation was confirmed.

The statewide average percentage of time when economizer is activated is highest in large office among the building types modeled. This is likely because of relatively smaller heat loss per unit floor area through the envelope of large offices and because large offices in California are more often in Coastal locations with mild weather that favor economizer use.

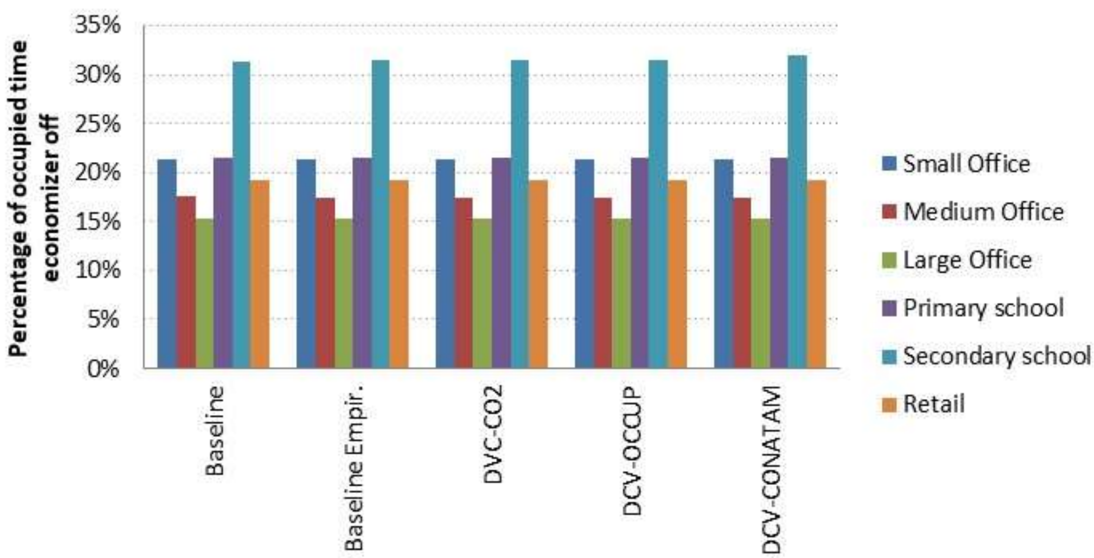
The exact cause of the large difference in economizer use between the secondary and primary school was unknown, however the two models do have different outdoor air control strategies, with the larger secondary school allowing a heat recovery bypass when the OA flow is greater than the minimum OA.

Underlying the presumed energy savings from applying DCV is the idea that during periods when less ventilation is needed and the economizer is inactive, VRs will be reduced.

Figure A-18 and Figure A-19 gives the statewide time-average VRs for each building modeled. These results suggest that during periods when the economizer is off, VRs are reduced by the application of DCV.

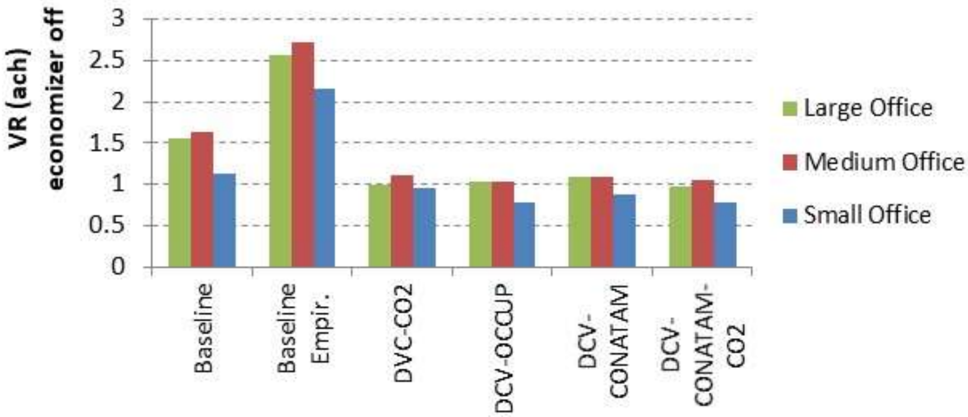
Small, medium, and large offices provide comparable VRs for each control strategy. The relatively small difference between office models was determined to be a consequence of the different internal heat gains in the basement levels of the medium and large offices where elevator equipment is modeled.

Figure A-17: Statewide Average Percentage of Occupied Time When Economizer is Deactivated



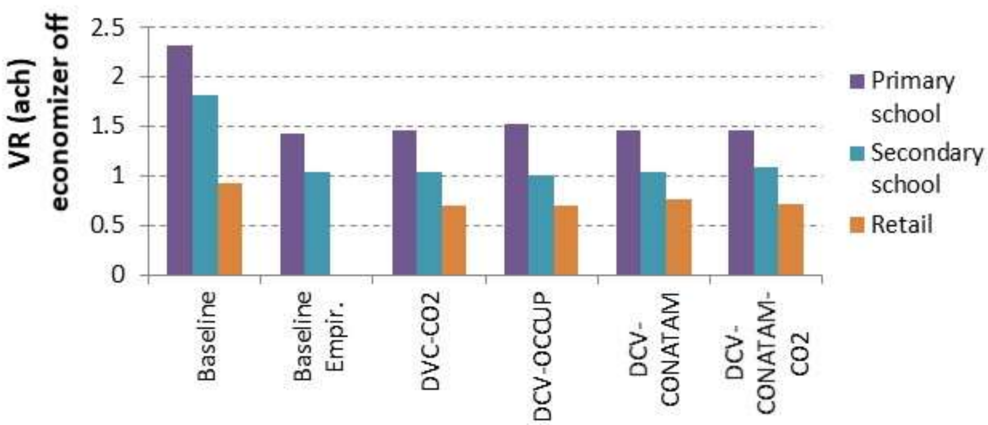
Source: Lawrence Berkeley National Laboratory

Figure A-18: Statewide Average Office Ventilation Rates When Economizer is Deactivated



Source: Lawrence Berkeley National Laboratory

Figure A-19: Statewide Average School and Retail Building Ventilation Rates When Economizer is Deactivated



Source: Lawrence Berkeley National Laboratory

APPENDIX B: Evaluation Testing of Outdoor Airflow Measurement Technologies

Reference Measurement

The major testing challenge was to obtain a highly accurate reference measurement of the outdoor airflow rate to which the air flow rate indicated by the outdoor airflow measurement technologies (OAMT) can be compared, while locating the OAMT outdoors so that the system is exposed to weather elements. For the reference measurements of outdoor airflow rates, the evaluation system includes a pair of different size nozzle airflow meters with upstream honeycomb airflow straighteners (NFM1 and NFM2), connected to research-grade pressure transducers (PTs). Sections of straight pipe upstream and downstream of the nozzle flow meters are provided in accordance with the manufacturer's specifications. Plates can be installed to prevent airflow through either nozzle flow meter, so that airflow can be measured using either the smaller, larger, or both nozzle flow meters, enabling the flow rates through the airflow meters to be maintained in the range that produces a pressure signal of sufficient magnitude for accurate measurement. A weather station located 3 m (10 ft.) above the rooftop, measures wind speed, wind direction, temperature, humidity, and atmospheric pressure. Table B-1 provides summary information on the key instruments and calibration procedures.

The rate of airflow through the nozzle flow meters was determined using the following equation:

$$F = A_e \sqrt{2\ \Delta P/\rho} \qquad (1)$$

where F is the actual flow rate in $m^3\ s^{-1}$, ρ is the density of the air in $kg\ m^{-3}$, ΔP is the pressure signal of the nozzle flow meter in Pa, A_e is the effective area of the nozzle in m^2, provided by the manufacturer. The values of Ae are 0.00857 m^2 and 0.0353 m^2 for the small and large nozzle flow meter, respectively. Air density was be calculated from:

$$\rho = \frac{P_{atm}}{R\,T}\ e^{(-9.8\,H)/(R\,T)} \qquad (2)$$

where P_{atm} is the atmospheric pressure, ρ is the density ($kg\ m^{-3}$), R is the gas constant for air ($J\ kg^{-1}\ K^{-1}$), T is the temperature in degrees Kelvin, and H is the altitude (m).

Table B-1: Key Instrumentation in Outside Airflow Measurement Technologies Evaluation System

Item	Make and Model	Range	Purpose	Manu-facturer's Rated Accuracy	Calibration or Performance Check
Small nozzle flow meter	Thermo-Brandt Instruments NZP-1031 (6 inch)	0.07–0.24 $m^3 s^{-1}$	Reference measurement of outdoor air flow rate	±0.5%	Compared to Pitot-static tube traverse in long straight duct
Large nozzle flow meter	Thermo-Brandt Instruments NZP-1031 (12 inch)	0.19–0.67 $m^3 s^{-1}$	Reference measurement of outdoor air flow rate	±0.5%	Compared to Pitot-static tube traverse in long straight duct
Multi-channel pressure transducer	Energy Conservatory APT-3-8	0–300 Pa and 0–1,000 Pa	Measure pressure signals of nozzle flow meters Measure airflow resistance of OAMT	± 1% of reading	Factory recalibration before deployment plus cross check with other instruments
Hot wire anemo-meter	TSI 9545	0–30 $m s^{-1}$	Check velocity profile in plane of the OAMT's airflow sensors	± 3% or ± 0.15 $m s^{-1}$	Factory calibration
Wind speed	Davis Instruments Vantage Vue Wireless Weather Station	3–241 km/h	Characterize outdoor weather conditions	± 3 km/h	Factory calibration
Wind direction	Davis Instruments Vantage Vue Wireless Weather Station	0–360º	Characterize outdoor weather conditions	± 3º	Factory calibration
Outdoor tempera-ture	Davis Instruments Vantage Vue Wireless Weather Station	-40–65ºC	Characterize outdoor weather conditions	± 0.5ºC	Factory calibration
Relative humidity	Davis Instruments Vantage Vue Wireless Weather Station	0–100%	Characterize outdoor weather conditions	± 3%	Factory calibration

Item	Make and Model	Range	Purpose	Manu-facturer's Rated Accuracy	Calibration or Performance Check
Atmo-spheric pressure	Davis Instruments Vantage Vue Wireless Weather Station	540–1100 mb	Characterize outdoor weather conditions	± 1 mb	Factory calibration
Air tempera-ture	Precision Thermistor Energy Conservatory APT-3-8	-40–100ºC	Characterize temperature of air in OAMT	± 0.25ºC (0–75ºC)	Factory Calibration

Source: Lawrence Berkeley National Laboratory

The key factors leading to uncertainty in the reference measurements of outdoor airflow rates (values of *F* in equation 1) were the uncertainty in the measurement of the pressure signal ΔP and the uncertainty in the effective area of the nozzle. The pressure signal of the pressure transducer connected to the nozzle airflow meters was maintained above 16 Pa. The rated accuracy of the pressure transducer is 1 percent of the measured value, i.e. 0.16 Pa at 16 Pa. Given the uncertainty in the process for checking the calibration of the pressure transducer, a higher pressure measurement uncertainty of ± 1.5 Pa was assumed, resulting in an associated uncertainty of ± 5 percent for the reference measurements of OA flow rate. The nozzle manufacturer lists an uncertainty of ± 0.5 percent, although the basis for this number is unclear. The uncertainty in air density was negligible. Adding these uncertainty components in quadrature led to a total estimated uncertainty of 5 percent for the reference measurements of outdoor airflow rates.

Figure B-1: OAMT Evaluation System Located on a LBNL Building Rooftop

(Left) Reference flow meters consisted of a smaller 6-inch nozzle and a larger 12-inch nozzle. (Right) Onsite weather station.

Source: Lawrence Berkeley National Laboratory

Figure B-2: Ruskin EAMS Installed with a Vertical-Bladed Louver

(Top) EAMS installed with a vertical-blade louver. (Bottom) The horizontal-blade louver is shown on the side of the system being tested.

Source: Lawrence Berkeley National Laboratory

Figure B-3: Ebtron Gold Probes Installed with Two Different Air Intake Hoods

(Top) Air intake hood design 1. (Bottom) Air intake hood design 2.

Source: Lawrence Berkeley National Laboratory

Detailed Test Results

Table B-2: Test Results of Electronic Air Measuring Station Installed with Horizontal-Blade Louver

Test	OA Damper Position	VFD (Hz)	Small Nozzle Flow Meter Position	Large Nozzle Flow Meter Position	Temp (ºC)	Wind Speed (m/s)	Reference Flow Meter (L/s) Mean	Reference Flow Meter (L/s) Std Dev	EAMS (L/s) Mean	EAMS (L/s) Std Dev	Static Pres. (Pa)
1	100%	60	OPEN	OPEN	20.5	2.4	1038	2.2	1057	18	107
2	100%	45	OPEN	OPEN	20.5	2.2	759	2.1	782	13	57
3	100%	30	OPEN	OPEN	21.0	2.2	476	1.8	479	14	22
4	100%	60	OPEN	OPEN	15.3	3.3	1038	1.3	1048	12	110
6	100%	30	OPEN	OPEN	16.8	3.0	474	2.5	455	18	22
7	100%	45	OPEN	OPEN	15.9	2.6	757	2.2	759	12	57
8	75%	22	OPEN	OPEN	19.3	3.0	319	3.8	277	14	10
9*	75%	22	OPEN	CLOSED	15.2	2.6	109	0.5	41	7.0	2
10	75%	40	OPEN	CLOSED	19.1	2.8	210	0.5	150	20	6
11	25%	40	OPEN	CLOSED	20.8	2.9	198	0.5	118	17	2
12*	25%	22	OPEN	CLOSED	26.4	0.4	105	0.2	66	4.9	1
13	25%	40	OPEN	CLOSED	27.2	0.8	199	0.3	171	8.4	4
14*	25%	22	OPEN	CLOSED	28.4	1.4	104	0.5	50	8.5	1
15*	75%	22	OPEN	CLOSED	28.9	1.4	110	0.4	54	7.8	1
16	75%	40	OPEN	CLOSED	31.1	1.5	212	0.4	160	16	4
17	25%	18	OPEN	OPEN	33.6	2.6	322	1.6	289	17	9
18	75%	22	OPEN	OPEN	27.2	0.2	335	1.4	331	4.7	10
19	25%	18	OPEN	OPEN	29.0	1.0	315	1.1	302	7.5	9

*** Excluded from error analysis because face velocity <0.5 m/s (manufacturer reported lower limit).**

Source: Lawrence Berkeley National Laboratory

Table B-3: Test Results of Electronic Air Measuring Station Installed with Vertical-Blade Louver

Test	**OA Damper Position**	**VFD (Hz)**	**Small Nozzle Flow Meter Position**	**Large Nozzle Flow Meter Position**	**Temp (ºC)**	**Wind Speed (m/s)**	**Reference Flow Meter (L/s)** Mean	**Reference Flow Meter (L/s)** Std Dev	**EAMS (L/s)** Mean	**EAMS (L/s)** Std Dev	**Static Pres. (Pa)**
20	100%	60	OPEN	OPEN	31.0	1.7	1078	2.5	1414	4.6	59
21	100%	45	OPEN	OPEN	31.7	1.8	788	1.8	1061	22	31
22	100%	30	OPEN	OPEN	32.2	2.0	496	1.3	675	21	11
23	75%	22	OPEN	OPEN	27.6	0.4	336	1.0	454	23	6
24	25%	35	OPEN	OPEN	28.3	0.7	331	0.9	454	18	6
25	100%	60	OPEN	OPEN	29.8	1.3	1076	2.1	1410	9.5	60
26	100%	45	OPEN	OPEN	29.9	1.6	789	2.1	1065	21	31
27	100%	30	OPEN	OPEN	29.7	0.7	497	1.3	685	19	13
28	75%	22	OPEN	OPEN	24.9	0.3	340	1.2	468	17	7
29	25%	35	OPEN	OPEN	24.1	0.6	368	1.8	508	15	7
30*	25%	22	OPEN	CLOSED	26.1	0.6	104	0.5	87	11	0.3
31	25%	40	OPEN	CLOSED	27.0	1.0	197	4.9	238	12	2
32*	75%	22	OPEN	CLOSED	27.8	1.3	111	0.6	94	8.1	0.2
33	75%	40	OPEN	CLOSED	26.9	1.2	212	0.4	250	14	2
34*	25%	22	OPEN	CLOSED	29.4	1.3	102	1.3	81	8.4	0.2
35	25%	40	OPEN	CLOSED	14.2	3.2	193	7.8	200	14	1
36*	75%	22	OPEN	CLOSED	15.1	3.6	111	0.6	85	5.6	1
37	75%	40	OPEN	CLOSED	15.8	4.2	212	0.5	223	7.7	2

*** Excluded from error analysis because face velocity <0.5 m/s (manufacturer reported lower limit).**

Source: Lawrence Berkeley National Laboratory

Table B-4: Test Results of Ebtron Gold Probes Installed with Air Intake Hood 2

Test	OA Damper Position	VFD (Hz)	Small Nozzle Flow Meter Position	Large Nozzle Flow Meter Position	Temp (ºC)	Wind Speed (m/s)	Reference Flow Meter (L/s) Mean	Reference Flow Meter (L/s) Std Dev	Ebtron (L/s) Mean	Ebtron (L/s) Std Dev	Static Pres. (Pa)
43	100%	60	OPEN	OPEN	22.5	1.6	1088	2.2	1149	36	—
44	100%	45	OPEN	OPEN	23.4	1.8	795	2.0	889	31	—
45	100%	30	OPEN	OPEN	15.2	0.4	505	1.8	586	25	7
46	25%	30	OPEN	OPEN	15.7	0.3	340	0.6	414	21	3
47	75%	22	OPEN	OPEN	18.5	1.0	341	1.5	458	25	4
48	25%	30	OPEN	OPEN	19.4	1.4	344	0.9	465	32	4
49	100%	30	OPEN	OPEN	20.6	1.8	497	2.1	627	26	8
50	100%	45	OPEN	OPEN	21.4	2.1	795	2.3	889	27	18
51	100%	60	OPEN	OPEN	20.0	1.8	1092	1.9	1148	33	33
52	75%	22	OPEN	OPEN	17.8	0.5	346	0.8	440	23	3
53	75%	22	OPEN	CLOSED	15.4	1.1	110	0.3	200	14	1
54	75%	40	OPEN	CLOSED	15.7	0.7	211	1.9	316	18	2
55	25%	40	OPEN	CLOSED	17.0	1.3	201	1.4	321	23	2
56	25%	22	OPEN	CLOSED	19.7	0.7	106	0.5	198	15	0.9
57	75%	22	OPEN	CLOSED	20.7	0.8	110	0.3	202	10	1
58	75%	40	OPEN	CLOSED	21.9	1.3	212	0.7	323	16	2
59	25%	40	OPEN	CLOSED	15.0	0.2	201	0.4	243	8.5	1
60	25%	22	OPEN	CLOSED	16.8	0.4	105	0.4	177	19	0.5

Source: Lawrence Berkeley National Laboratory

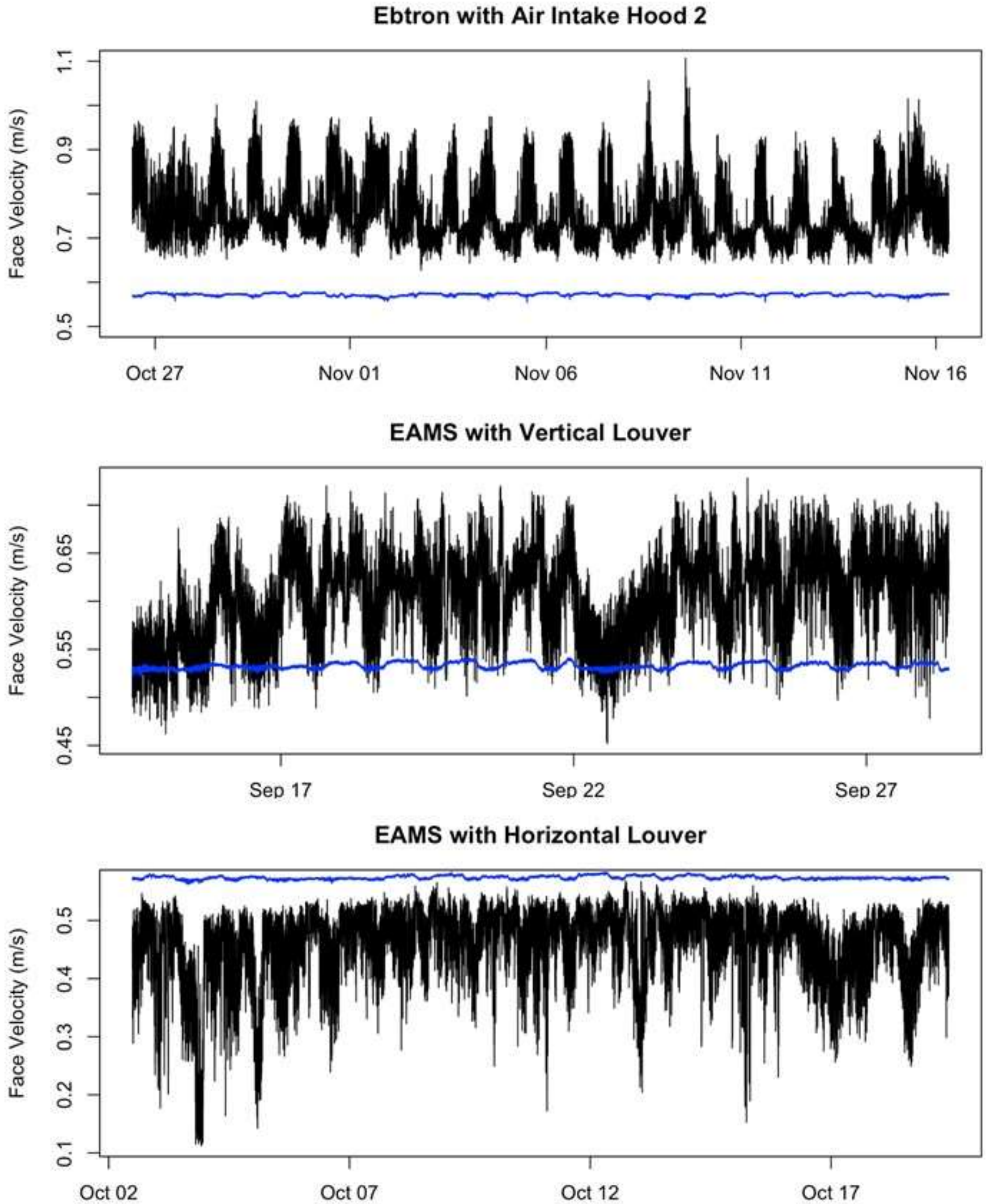
Table B-5: Test Results of Ebtron Gold Probes Installed with Air Intake Hood 1

Test	OA Damper Position	VFD (Hz)	Sm Noz. Flow Meter Position	Lg Noz Flow Meter Position	Temp (oC)	Wind Speed (m/s)	Reference Flow Meter (L/s) Mean	Reference Flow Meter (L/s) Std Dev	Ebtron (L/s) Mean	Ebtron (L/s) Std Dev	Static Pres. (Pa)
62	100%	60	OPEN	OPEN	8.2	1.1	1117	1.7	1062	47	13
63	100%	45	OPEN	OPEN	10.3	0.9	813	2.1	829	44	7
64	100%	30	OPEN	OPEN	12.3	1.0	514	22	587	35	3
65	100%	60	OPEN	OPEN	13.0	1.3	1116	3.9	1042	35	15
66	100%	45	OPEN	OPEN	14.1	1.2	818	1.4	850	41	7
67	100%	30	OPEN	OPEN	14.8	0.8	511	1.4	543	29	4
68	25%	30	OPEN	OPEN	11.5	0.6	334	1.9	390	30	1
69	25%	30	OPEN	OPEN	11.7	1.0	331	0.9	390	29	1
70	25%	22	OPEN	CLOSED	12.5	0.9	112	17	176	19	0.4
71	25%	40	OPEN	CLOSED	13.4	0.7	199	0.3	247	10	2
72	25%	22	OPEN	CLOSED	14.3	1.0	105	0.3	168	13	1
73	25%	40	OPEN	CLOSED	13.7	0.6	199	0.3	239	10	1
74	75%	22	OPEN	CLOSED	11.8	4.1*	112	15	231	34	2
75	75%	40	OPEN	CLOSED	11.3	4.6*	210	0.5	314	35	3
76	75%	22	OPEN	CLOSED	12.9	4.9*	108	1.2	256	47	3
77	75%	40	OPEN	CLOSED	11.4	4.7*	209	0.6	318	37	3
78	25%	40	OPEN	CLOSED	9.6	0.0	201	0.6	226	14	0.9
79	25%	22	OPEN	CLOSED	9.8	0.4	106	0.2	149	9.0	0.3
80	75%	22	OPEN	CLOSED	10.1	0.6	111	6.6	156	12	0.4
81	75%	40	OPEN	CLOSED	11.3	0.9	209	7.4	276	34	0.8
82	75%	22	OPEN	OPEN	12.5	1.5	342	2.0	416	36	2
83	75%	22	OPEN	OPEN	12.5	1.7	342	2.0	419	29	2

*** Periods of high wind relative to the other tests.**

Source: Lawrence Berkeley National Laboratory

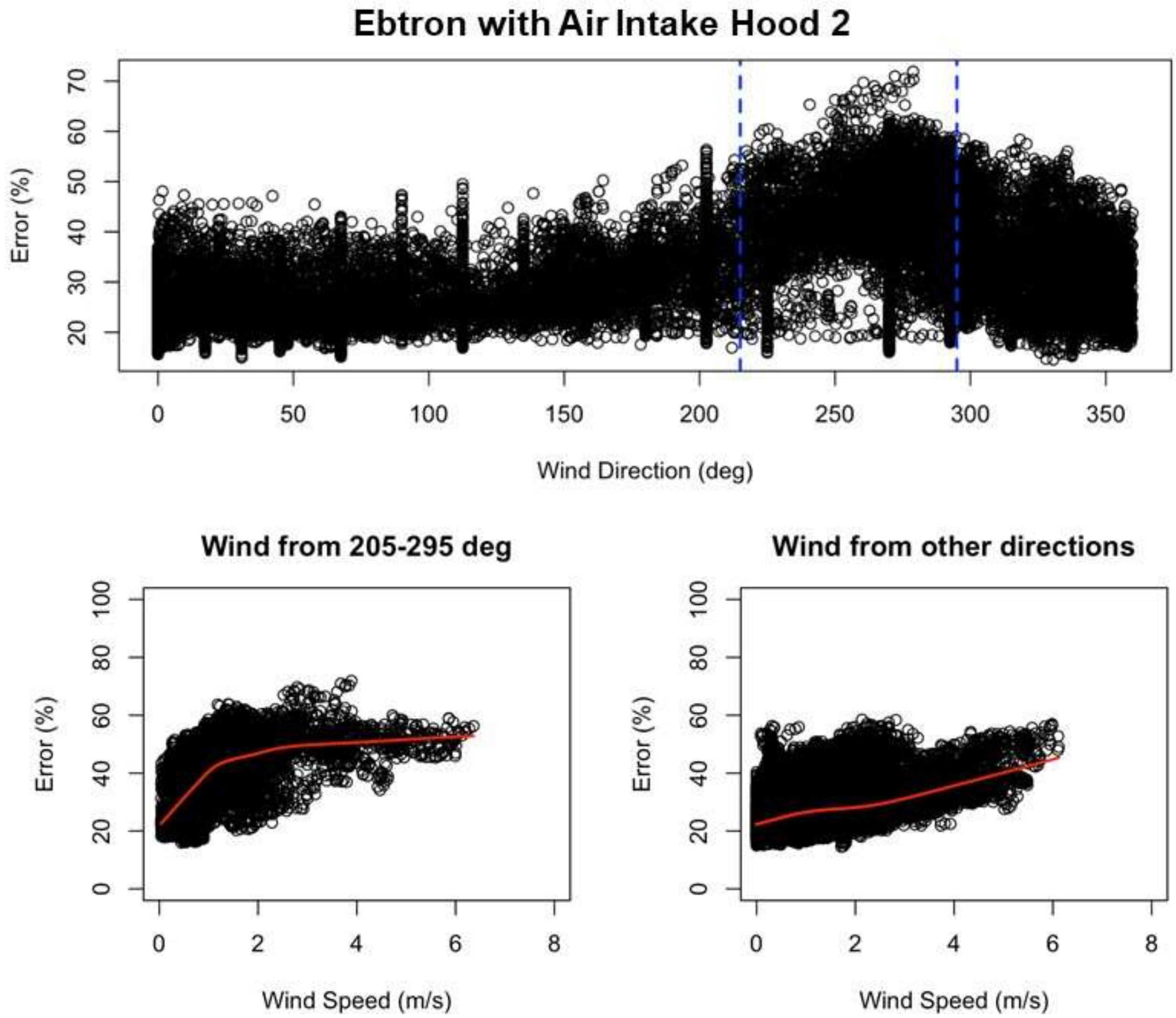
Figure B-4: Two-Week Measurements by OAMTs



Reference measurements by airflow meter shown in blue for comparison.

Source: Lawrence Berkeley National Laboratory

Figure B-5: Effects of Wind on Measurement Error of Ebtron Gold Probe System Tested with Air Intake Hood 2



Measurement errors plotted as a function of wind directions (top), and wind speeds (bottom two panels) when wind was blowing from different directions. The red line traces the trend suggested by the data points using lowess function of R statistical software.

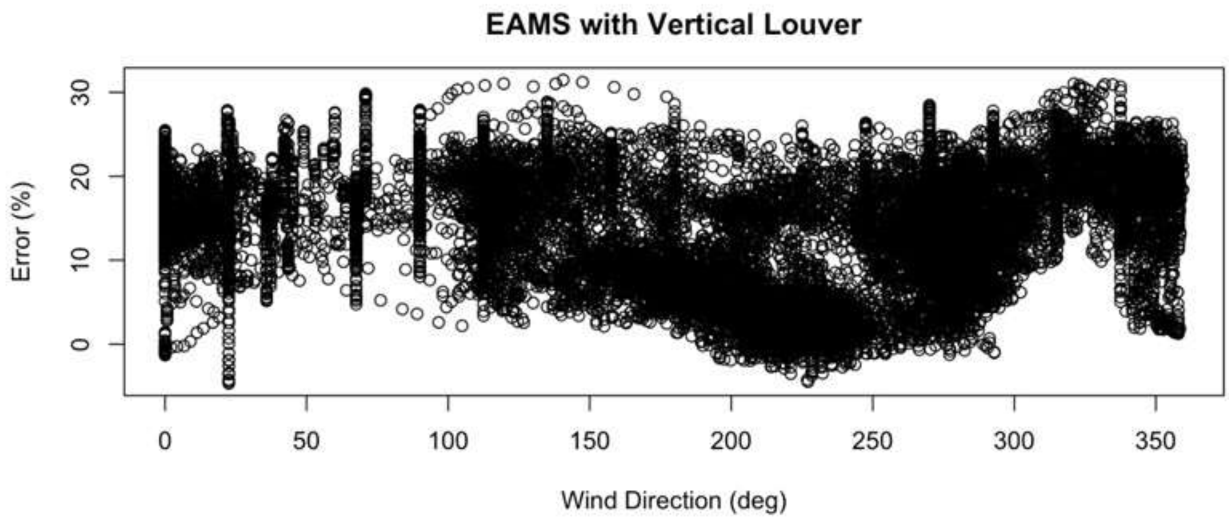
Source: Lawrence Berkeley National Laboratory

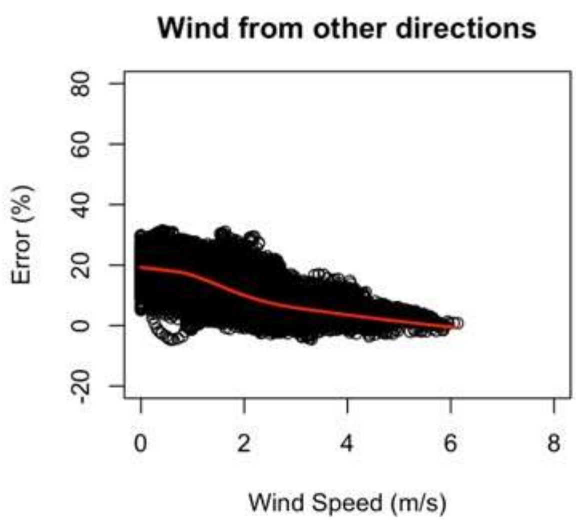
Table B-6: Regression Results Showing Effects of Wind Speed on Measurement Errors of Ebtron Gold Probe System Tested with Air Intake Hood 2

	Intercept (Std. Error)	Slope (Std. Error)	R^2
Wind from 205 to 295 degree	33.97 (0.18)	5.44 (0.10)	0.26
Wind from other directions	24.06 (0.07)	3.05 (0.04)	0.19

Figure B-6: Effects of Wind on Measurement Error of EAMS

Described in text.





Measurement errors plotted as a function of wind directions (top), and wind speeds (bottom). The red line traces the trend suggested by the data points using lowess function of R statistical software.

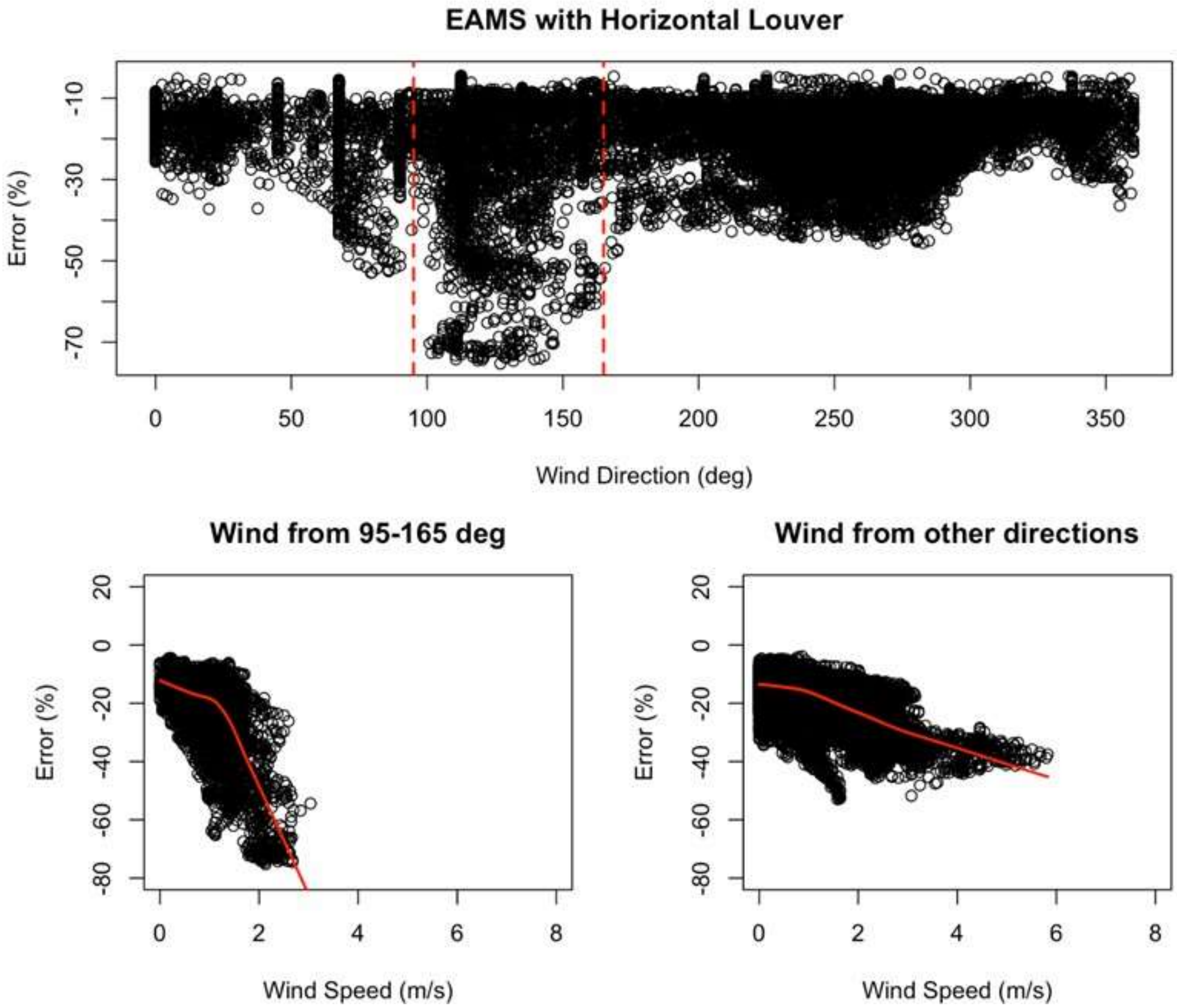
Source: Lawrence Berkeley National Laboratory

Table B-7: Regression Results Showing Effects of Wind Speeds on Measurement Error of Electronic Air Measuring Station Tested with a Vertical Louver

	Intercept (Std. Error)	Slope (Std. Error)	R^2
Wind from all directions	20.10 (0.06)	-4.36 (0.03)	0.51

Source: Lawrence Berkeley National Laboratory

Figure B-7: Effects of Wind on Measurement Error by EAMS Tested with a Horizontal Louver



Measurement errors plotted as a function of wind directions (top), and wind speeds (bottom two panels) when wind was blowing from different directions. The red line traces the trend suggested by the data points using lowess function of R statistical software.

Source: Lawrence Berkeley National Laboratory

Table B-8: Regression Results Showing Effects of Wind Speeds on Measurement Error of Electronic Air Measuring Station Tested with a Horizontal Louver

	Intercept (Std. Error)	Slope (Std. Error)	R^2
Wind from 95 to 165 degree	-5.68 (0.34)	-17.47 (0.31)	0.40
Wind from other directions	-11.94 (0.08)	-5.65 (0.05)	0.39

Source: Lawrence Berkeley National Laboratory

APPENDIX C: Carbon Dioxide Sensor Accuracy

Carbon Dioxide Reference Measurement

Table C-1 shows the regression results from each accuracy check, where the slope and intercept were determined using a linear fit between the concentrations measured by EGM4 and calibration bags. From the linear fit, the researchers predicted EGM4 concentration if the true CO_2 concentration was 1,000 ppm, and the corresponding standard error of the prediction.

EGM4 readings were very close to true CO_2 concentration on average, where the mean (± standard error) predicted concentration was 1002 (±2) ppm for the office, 1001 (±2) ppm for the conference room, and 1002 (±2) ppm for the classroom. Based on these results, the researchers conclude that the CO_2 concentrations measured by the EGM4 were close approximations of the true CO_2 concentration for this evaluation study.

Table C-1: Carbon Dioxide Reference Instrument Accuracy Checks

	Date	Office Slope	Office Inter-cept	Office R^2	Office Pred. ppm	Office Std. Err.	Conference Room Slope	Conference Room Inter-cept	Conference Room R^2	Con-ference Room Pred. ppm	Con-ference Room Std. Err.	Class room Slope	Class room Inter-cept	Class room R^2	Class room Pred. ppm	Class room Std. Err.
1	2015-03-05	0.99	6.6	1.000	1,000	3.8	0.99	8.5	1.000	996	3.0	0.99	0.3	1.000	986	3.6
2	2015-03-13	0.99	9.7	1.000	1,003	3.2	1.00	5.0	1.000	1009	1.6	0.98	-5.0	1.000	977	3.7
3	2015-03-27	1.00	17.3	1.000	1,013	4.9	1.00	12.4	1.000	1013	3.6	1.00	-1.0	1.000	1,000	5.7
4	2015-04-10	1.01	8.2	1.000	1,015	1.4	1.00	13.8	1.000	1012	2.9	1.00	5.8	1.000	1011	1.7
5	2015-04-24	1.00	5.1	1.000	1,003	1.5	1.00	9.1	1.000	1005	2.0	1.00	4.3	1.000	1003	1.4
6	2015-05-08	1.00	6.4	1.000	1,007	0.7	1.01	-5.5	1.000	1002	4.8	1.00	8.6	1.000	1007	2.1
7	2015-05-22	1.00	9.1	1.000	1,010	1.0	1.00	4.5	1.000	1008	1.7	1.00	10.9	1.000	1007	1.7
8	2015-06-05	1.00	7.0	1.000	1,005	1.2	1.00	6.3	1.000	1007	1.7	1.00	11.3	1.000	1007	1.5
9	2015-06-25	1.00	4.5	1.000	1,003	1.1	1.00	5.8	1.000	1007	1.0	1.00	5.0	1.000	1006	1.9
10	2015-07-22	0.99	5.7	1.000	991	2.2	0.99	9.2	1.000	999	3.2	0.99	5.9	1.000	993	3.2
11	2015-08-21	1.00	1.1	1.000	1,001	0.9	1.00	4.3	1.000	1005	1.2	0.99	6.9	1.000	1002	1.8
12	2015-09-25	1.00	1.7	1.000	1,002	1.3	1.00	1.8	1.000	1,000	0.8	1.00	4.0	1.000	1003	1.7
13	2015-10-23	1.00	-2.0	1.000	1,000	2.2	1.00	-1.2	1.000	999	2.7	1.00	-0.9	1.000	1,000	2.5
14	2015-11-23	1.00	0.9	1.000	998	1.7	1.00	4.4	1.000	1001	2.1	0.99	4.1	1.000	998	1.7
15	2015-12-18	1.00	1.8	1.000	1,004	0.9	1.00	6.2	1.000	1003	2.2	1.00	4.9	1.000	1003	1.4

	Date	Office Slope	Office Inter-cept	Office R^2	Office Pred. ppm	Office Std. Err.	Confe rence Room Slope	Confe rence Room Inter-cept	Confer ence Room R^2	Con-ference Room Pred. ppm	Con-ference Room Std. Err.	Class room Slope	Class room Inter-cept	Class room R^2	Class room Pred. ppm	Class room Std. Err.
16	2016-01-28	0.99	6.6	1.000	998	2.3	0.99	6.9	1.000	998	1.9	0.99	7.2	1.000	1,000	2.6
17	2016-02-26	1.00	-3.5	1.000	999	2.1	0.99	1.7	1.000	995	1.8	1.00	0.0	1.000	999	2.5
18	2016-03-23	1.00	1.6	1.000	1,002	1.1	1.00	4.1	1.000	1002	1.7	1.00	4.9	1.000	1,000	1.3
19	2016-04-22	1.01	-0.6	1.000	1,005	0.9	1.00	6.5	1.000	1009	2.3	0.99	4.7	1.000	999	1.3
20	2016-05-25	0.99	6.5	1.000	1,000	1.9	0.99	6.4	1.000	992	2.0	1.01	5.2	1.000	1014	1.9
21	2016-06-10	1.00	-2.9	1.000	997	1.3	0.99	4.5	1.000	994	1.5	1.00	3.5	1.000	1005	0.9
22	2016-06-29	1.00	-0.6	1.000	998	0.8	1.00	4.6	1.000	1008	1.9	1.00	6.2	1.000	1007	1.6
23	2016-07-29	1.00	3.6	1.000	999	1.2	1.00	6.0	1.000	1007	2.1	NA	NA	NA	NA	NA
24	2016-08-31	1.00	0.9	1.000	998	0.9	1.00	4.6	1.000	1,000	1.1	1.00	6.9	1.000	1007	1.9
25	2016-09-30	1.00	0.2	1.000	998	0.6	1.00	6.8	1.000	1003	2.2	1.00	2.4	1.000	1004	1.4
26	2016-10-31	1.00	0.4	1.000	996	1.0	0.99	-1.9	1.000	991	1.9	1.00	4.1	1.000	1005	1.5
27	2016-11-28	1.00	-1.2	1.000	995	1.3	1.00	-1.3	1.000	997	2.1	1.00	3.2	1.000	1004	1.6
28	2017-01-05	1.00	-0.5	1.000	996	0.6	1.00	-2.7	1.000	995	2.0	1.00	2.9	1.000	1002	1.2
29	2017-02-03	1.00	-0.7	1.000	995	0.9	1.00	-3.7	1.000	995	2.1	1.00	3.5	1.000	1003	1.3
30	2017-03-06	1.00	-2.0	1.000	994	0.8	1.00	-3.8	1.000	995	2.2	1.00	-0.1	1.000	999	0.7

Source: Lawrence Berkeley National Laboratory

Carbon Dioxide Sensor Accuracy Test Results

Table C-2: Carbon Dioxide Sensor Measurement Errors Evaluated in an Office Space

CO_2 Sensors (3 replicates each)	Error (ppm) Mean	Error (ppm) Standard Deviation	Absolute Value of Error (ppm) Mean	Absolute Value of Error (ppm) Standard Deviation	% of Time Abs. Error <75 ppm	% of Time Abs. Error <100 ppm
GMW86	-30	14	30	14	98%	100%
GMW86	-21	14	21	14	98%	100%
GMW86	-26	14	26	14	98%	100%
TR9294	-7	17	14	12	100%	100%
TR9294	-15	15	16	14	100%	100%
TR9294	-9	16	13	13	100%	100%
ACD05	-24	27	29	22	96%	99%
ACD05	-17	23	21	20	98%	99%
ACD05	-28	21	29	20	97%	99%
DCD05	-61	24	61	24	77%	94%
DCD05	52	31	54	28	80%	94%
DCD05	-50	30	51	26	85%	97%
T8100	-12	15	14	13	99%	100%
T8100	-13	16	15	14	99%	100%
T8100	-1	15	11	10	100%	100%
T8200	-47	31	49	28	81%	94%
T8200	-10	30	20	24	97%	99%
T8200	-65	23	65	23	69%	94%
COZIR	99	45	99	45	31%	59%
COZIR	77	32	77	32	42%	76%
COZIR	97	43	98	42	31%	47%

Reference CO_2 Concentration = 700 ppm

Source: Lawrence Berkeley National Laboratory

Table C-3: Carbon Dioxide Sensor Measurement Errors Evaluated in Conference Room (Reference CO_2 Concentration = 700 ppm)

CO_2 Sensors (3 replicates each)	Error (ppm) Mean	Error (ppm) Std. Dev.	Absolute Value of Error (ppm) Mean	Absolute Value of Error (ppm) Std. Dev.	% of Time Abs. Error <75 ppm	% of Time Abs. Error <100 ppm
GMW86	-28	22	30	19	97%	99%
GMW86	-34	21	35	19	97%	99%
GMW86	-33	21	34	19	97%	99%
TR9294	-22	25	26	20	97%	99%
TR9294	-20	25	24	21	97%	99%
TR9294	-31	28	34	24	95%	99%
ACD05	11	58	43	40	84%	91%
ACD05	-54	46	61	37	76%	88%
ACD05	-45	48	54	38	81%	89%
DCD05	-66	47	71	39	61%	83%
DCD05	-67	48	71	41	61%	82%
DCD05	-60	58	70	46	63%	77%
T8100	-21	28	27	23	97%	99%
T8100	-17	29	25	22	97%	99%
T8100	1	30	20	22	98%	100%
T8200	-35	38	42	30	88%	96%
T8200	4	42	31	29	92%	97%
T8200	-43	42	51	33	80%	94%
COZIR	88	59	91	55	43%	60%
COZIR	75	42	78	37	44%	76%
COZIR	78	67	90	48	39%	58%

Source: Lawrence Berkeley National Laboratory

Table C-4: Carbon Dioxide Sensor Measurement Errors Evaluated in Conference Room (Reference CO_2 Concentration = 1,000 ppm)

CO_2 Sensors (3 replicates each)	Error (ppm) Mean	Error (ppm) Std. Dev.	Absolute Value of Error (ppm) Mean	Absolute Value of Error (ppm) Std. Dev.	% of Time Abs. Error <75 ppm	% of Time Abs. Error <100 ppm
GMW86	-25	47	39	37	89%	95%
GMW86	-45	41	49	35	82%	95%
GMW86	-34	45	43	37	86%	94%
TR9294	-10	43	29	33	94%	98%
TR9294	-9	43	29	33	94%	98%
TR9294	-20	49	39	36	87%	96%
ACD05	34	91	76	61	62%	75%
ACD05	-80	74	89	64	53%	67%
ACD05	-60	77	73	64	63%	76%
DCD05	-105	80	112	70	29%	52%
DCD05	-105	78	110	69	30%	52%
DCD05	-85	90	98	75	43%	60%
T8100	-18	49	37	37	89%	96%
T8100	-14	47	34	35	90%	95%
T8100	12	47	34	35	91%	96%
T8200	-18	60	47	41	81%	90%
T8200	26	65	52	47	79%	86%
T8200	-21	62	47	46	78%	89%
COZIR	126	73	127	70	25%	41%
COZIR	106	56	108	51	23%	42%
COZIR	83	81	98	61	38%	58%

Source: Lawrence Berkeley National Laboratory

Table C-5: Carbon Dioxide Sensor Measurement Errors Evaluated in a Classroom (Reference CO_2 Concentration = 700 ppm)

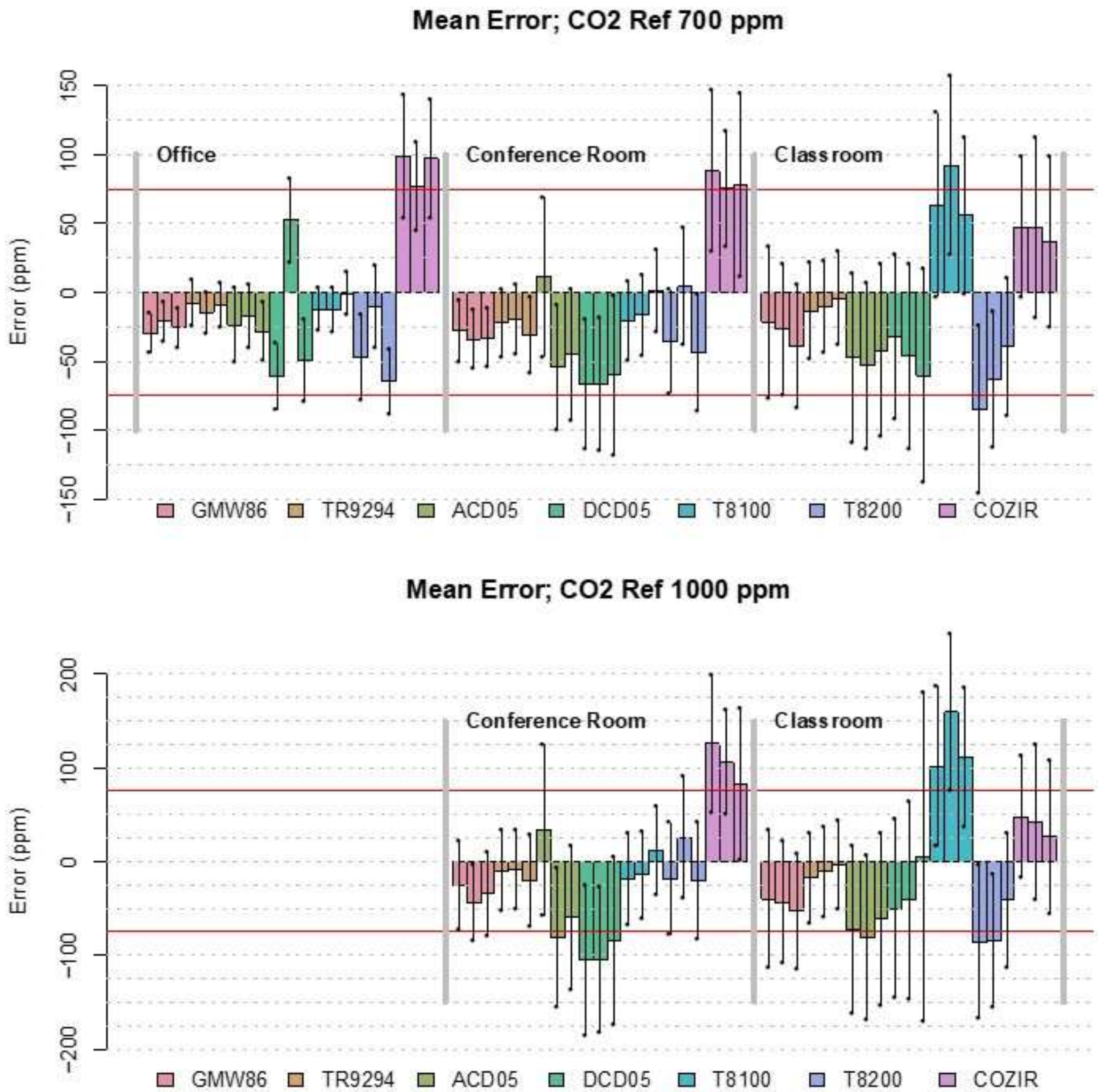
CO_2 Sensors (3 replicates each)	Error (ppm) Mean	Error (ppm) Std. Dev.	Absolute Value of Error (ppm) Mean	Absolute Value of Error (ppm) Std. Dev.	% of Time Abs. Error <75 ppm	% of Time Abs. Error <100 ppm
GMW86	-21	55	43	41	83%	93%
GMW86	-27	47	42	35	85%	94%
GMW86	-39	45	48	35	79%	92%
TR9294	-13	35	27	26	95%	98%
TR9294	-10	33	25	24	96%	99%
TR9294	-4	34	24	25	96%	99%
ACD05	-47	61	62	47	68%	81%
ACD05	-53	60	66	46	67%	80%
ACD05	-42	63	59	47	71%	83%
DCD05	-32	60	51	45	76%	85%
DCD05	-46	67	65	49	65%	78%
DCD05	-60	78	80	58	55%	71%
T8100	63	67	69	61	67%	81%
T8100	92	65	95	61	36%	61%
T8100	56	57	64	47	69%	83%
T8200	-85	61	93	48	38%	60%
T8200	-63	50	70	40	59%	78%
T8200	-40	50	52	37	76%	88%
COZIR	47	51	59	38	69%	86%
COZIR	47	65	68	44	61%	78%
COZIR	37	62	59	41	68%	84%

Source: Lawrence Berkeley National Laboratory

Table C-6: Carbon Dioxide Sensor Measurement Errors Evaluated in a Classroom (Reference CO_2 Concentration = 1,000 ppm)

CO_2 Sensors (3 replicates each)	Error (ppm) Mean	Error (ppm) Std. Dev.	Absolute Value of Error (ppm) Mean	Absolute Value of Error (ppm) Std. Dev.	% of Time Abs. Error <75 ppm	% of Time Abs. Error <100 ppm
GMW86	-40	74	67	50	62%	79%
GMW86	-43	65	65	44	63%	80%
GMW86	-52	62	68	45	60%	77%
TR9294	-18	48	37	35	90%	96%
TR9294	-11	47	34	34	92%	97%
TR9294	-3	48	32	35	93%	97%
ACD05	-73	90	97	63	41%	55%
ACD05	-82	87	103	62	38%	52%
ACD05	-61	91	90	63	46%	58%
DCD05	-50	96	85	67	50%	61%
DCD05	-41	106	89	70	49%	60%
DCD05	5	176	123	126	40%	53%
T8100	102	86	103	84	43%	62%
T8100	160	84	160	83	9%	22%
T8100	111	75	112	73	33%	48%
T8200	-86	82	103	58	34%	50%
T8200	-85	70	97	51	34%	52%
T8200	-41	72	68	48	59%	76%
COZIR	48	65	64	50	65%	81%
COZIR	42	83	75	54	56%	70%
COZIR	26	82	65	56	65%	77%

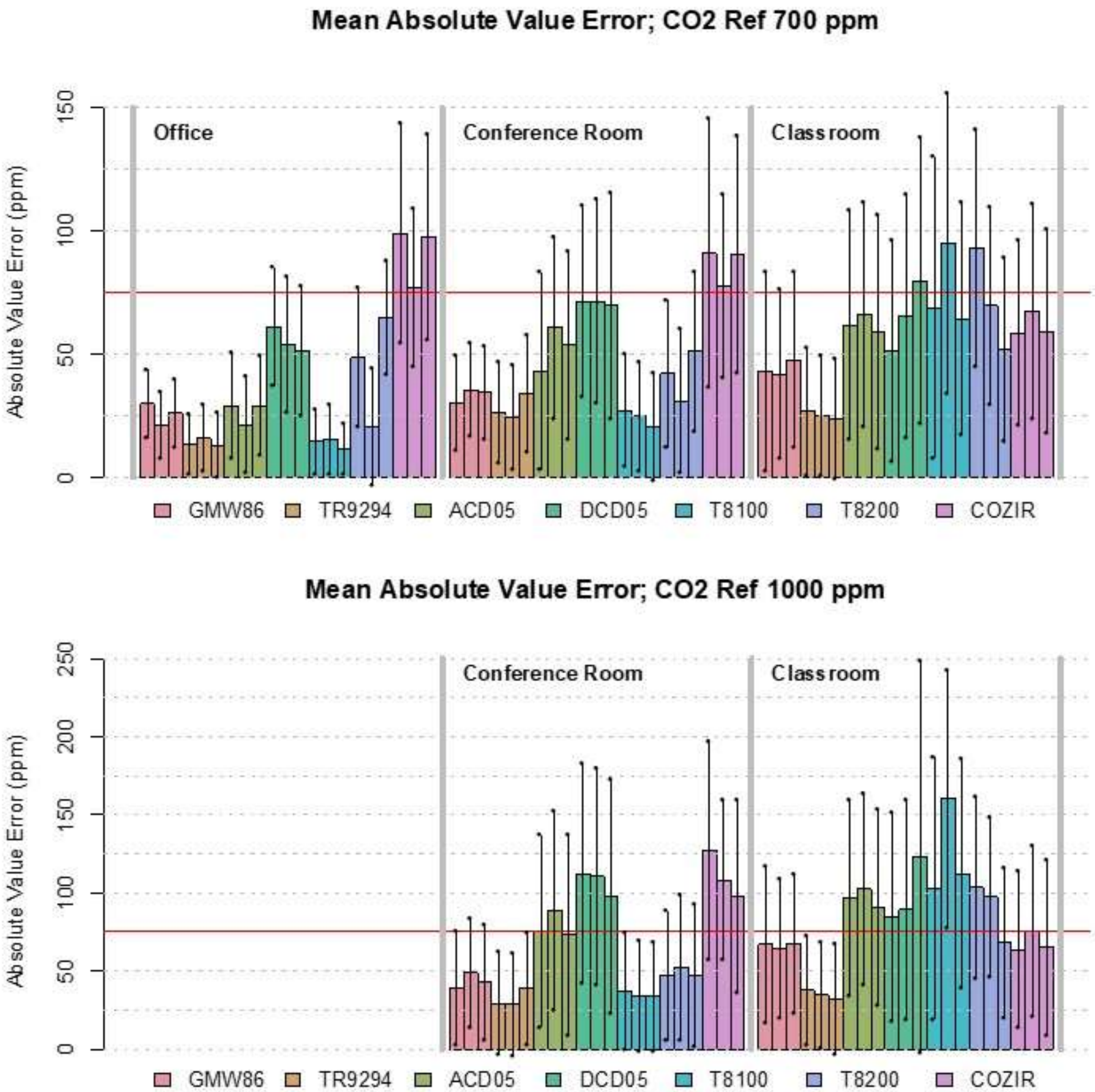
Figure C-1: Carbon Dioxide Sensor Measurement Errors



Upper plot shows CO_2 sensor measurement errors evaluated at reference concentration of 700 ppm. Lower plot shows measurement errors at 1,000 ppm. CO_2 concentrations measured in office did not reach 1,000 ppm, thus results are not available in the lower plot. Bars showing mean error, overlying lines show ± standard deviation. Red lines show ±75 ppm accuracy requirement per Title 24 as a point of reference.

Source: Lawrence Berkeley National Laboratory

Figure C-2: Carbon Dioxide Sensor Absolute Value of Measurement Errors



Upper plot shows CO_2 sensor measurement errors evaluated at reference concentration of 700 ppm. Lower plot shows measurement errors at 1,000 ppm. CO_2 concentrations measured in office did not reach 1,000 ppm, thus results are not available in the lower plot. Bars showing mean absolute value of measurement error, overlying lines show ± standard deviation. Red lines show ±75 ppm accuracy requirement per Title 24 as a point of reference.

Source: Lawrence Berkeley National Laboratory

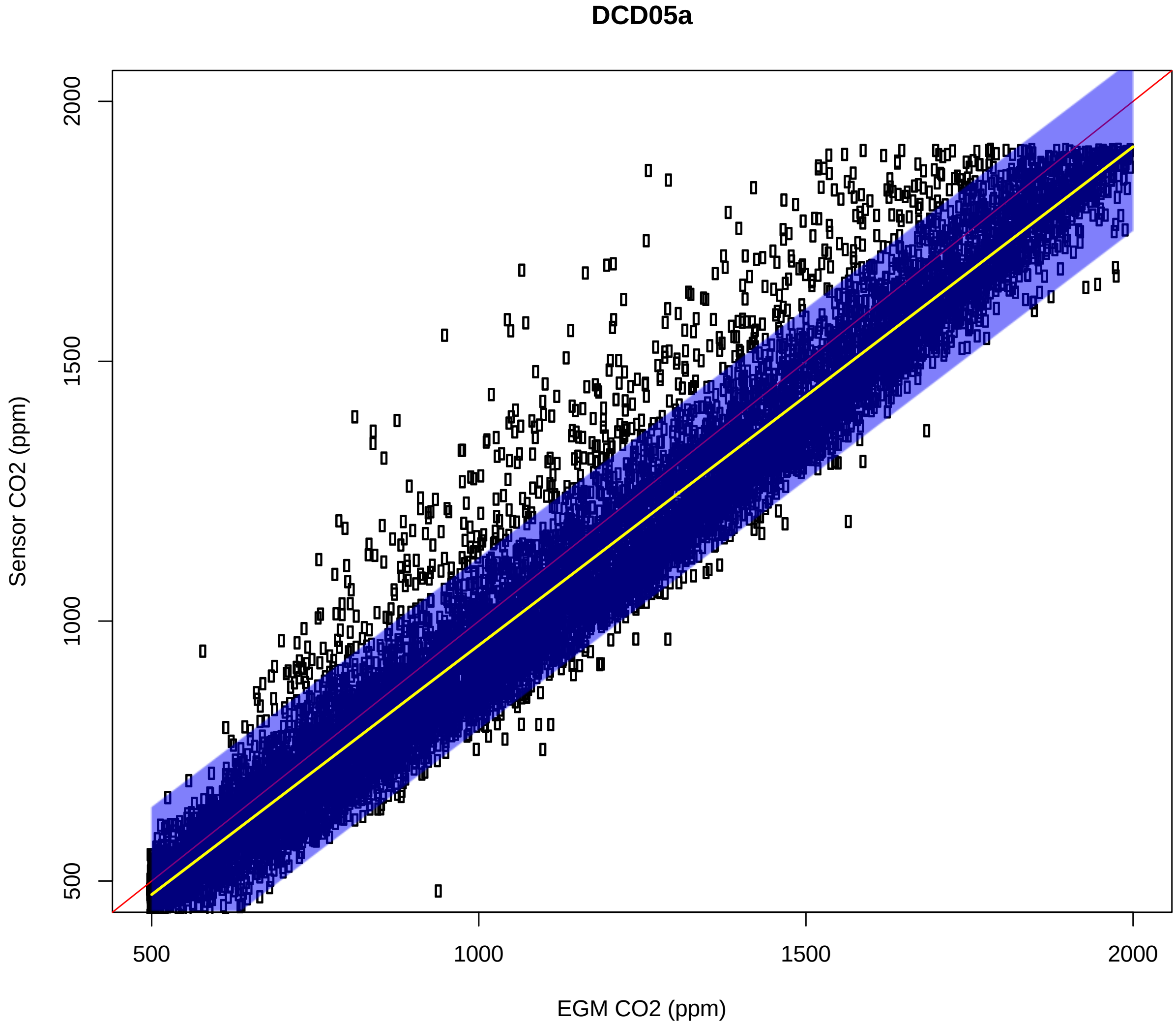
Table C-7: Results of Linear Regression Fit Between Carbon Dioxide Sensor Readings and Reference Instrument

	Office Slope	Office Intercept	Office R^2	Conf. Rm. Slope	Conf. Rm. Intercept	Conf. Rm. R^2	Conf. Rm. Slope	Conf. Rm. Intercept	Conf. Rm. R^2
GMW86	0.96	-2.4	0.93	0.97	-3.4	0.97	0.95	11.6	0.97
GMW86	0.97	2.0	0.93	0.95	3.1	0.98	0.95	5.7	0.98
GMW86	0.95	10.3	0.93	0.96	-7.1	0.98	0.96	-13.3	0.98
TR9294	0.92	43.9	0.91	0.99	-13.6	0.97	0.99	-4.9	0.99
TR9294	0.93	31.9	0.92	0.98	-6.6	0.97	1.00	-10.1	0.99
TR9294	0.93	38.1	0.90	0.97	-4.8	0.97	1.01	-10.0	0.99
ACD05	0.85	72.9	0.77	1.07	-35.0	0.89	0.86	52.8	0.95
ACD05	0.96	8.6	0.86	0.88	31.3	0.91	0.85	58.7	0.95
ACD05	0.90	37.3	0.85	0.91	22.0	0.90	0.88	50.2	0.95
DCD05	0.93	-12.8	0.85	0.88	17.3	0.89	0.96	-5.6	0.95
DCD05	1.06	13.7	0.80	0.91	-2.9	0.89	1.00	-39.6	0.95
DCD05	0.95	-14.2	0.77	0.90	10.4	0.84	1.42*	-357*	0.88*
T8100	0.88	66.8	0.91	0.95	14.5	0.96	1.07	16.2	0.97
T8100	0.86	80.5	0.89	0.96	13.0	0.96	1.17	-25.9	0.97
T8100	0.90	69.1	0.89	1.00	2.4	0.96	1.13	-32.3	0.97
T8200	0.93	-0.7	0.79	1.01	-40.1	0.94	0.93	-32.4	0.96
T8200	0.96	14.9	0.80	1.03	-12.5	0.93	0.95	-33.1	0.97
T8200	0.95	-28.4	0.87	1.05	-76.1	0.93	0.99	-33.0	0.97
COZIR	1.02	79.1	0.67	1.08	35.5	0.87	0.98	65.0	0.98
COZIR	0.93	123.5	0.74	1.05	43.3	0.93	0.98	60.0	0.96
COZIR	0.96	120.2	0.63	0.98	97.5	0.82	0.98	46.6	0.96

*** With the exception of one case: DCD05 (3rd replicate, see Figure C-3) in classroom, the linear equation generally describes the relationship between CO_2 sensors and the reference concentrations. We found no obvious reason that may explain the nonlinearity of this one case. Higher R^2 was obtained from linear fit using classroom data than the other two spaces. This is because classroom CO_2 concentrations span a wider range in values (>2000 ppm) than in the office (700 ppm maximum) or conference room (1,000 to 1500 ppm when occupied).**

Source: Lawrence Berkeley National Laboratory

Figure C-3: Carbon Dioxide Sensor DCD05 (Telaire 8200, a Set of 3 Replicates) Evaluated in a Classroom

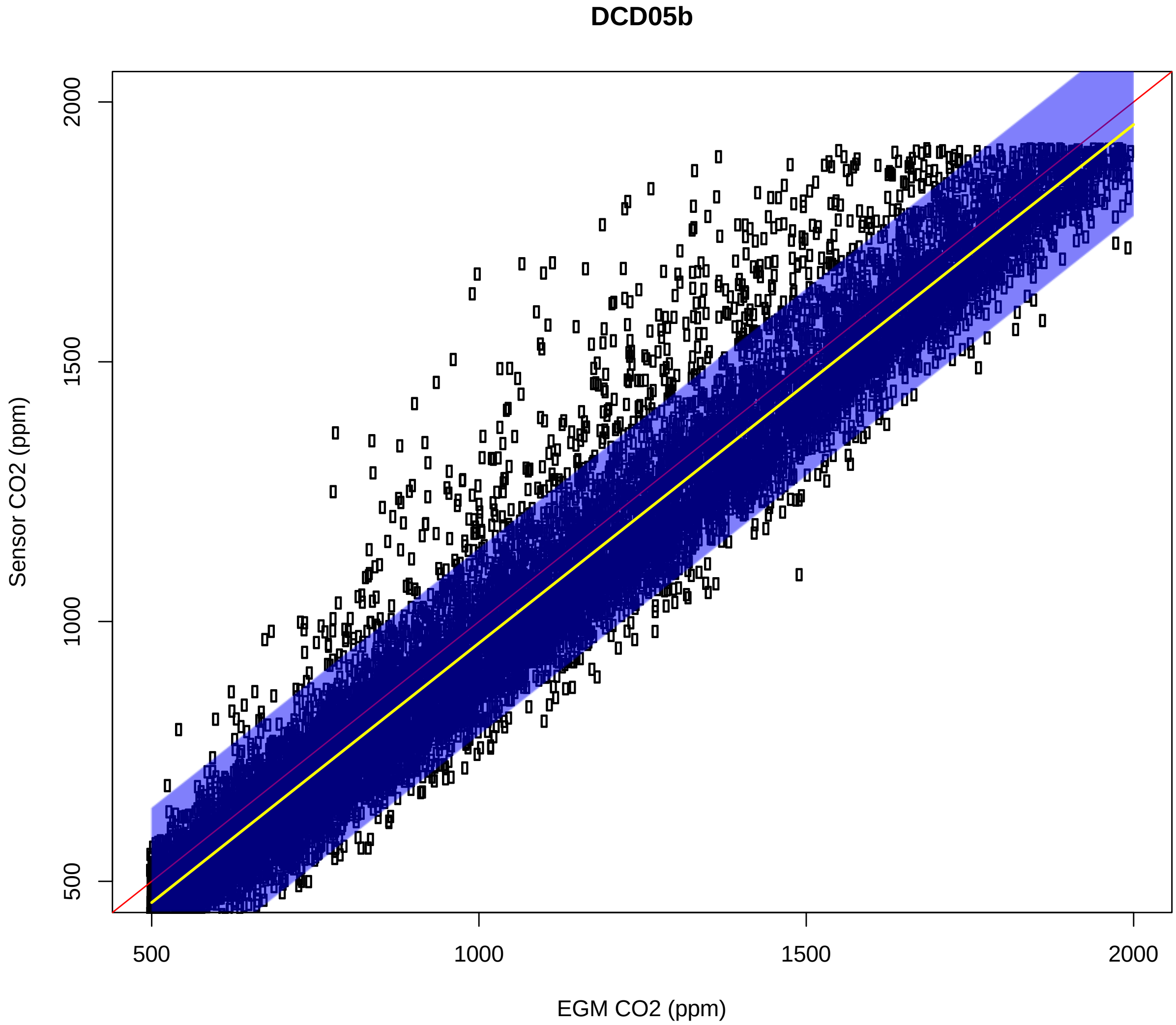


This and subsequent two plots show both linear (DCD05a, DCD05b) and nonlinear (DCD05c) response with respect to the reference CO_2 measurement.

For presentation purposes, this plot and subsequent scattered plots show 10 percent of the data collected (selected randomly). The yellow line shows the linear regression results; area shaded in blue is the 95 percent prediction interval. The 1:1 line is indicated in red.

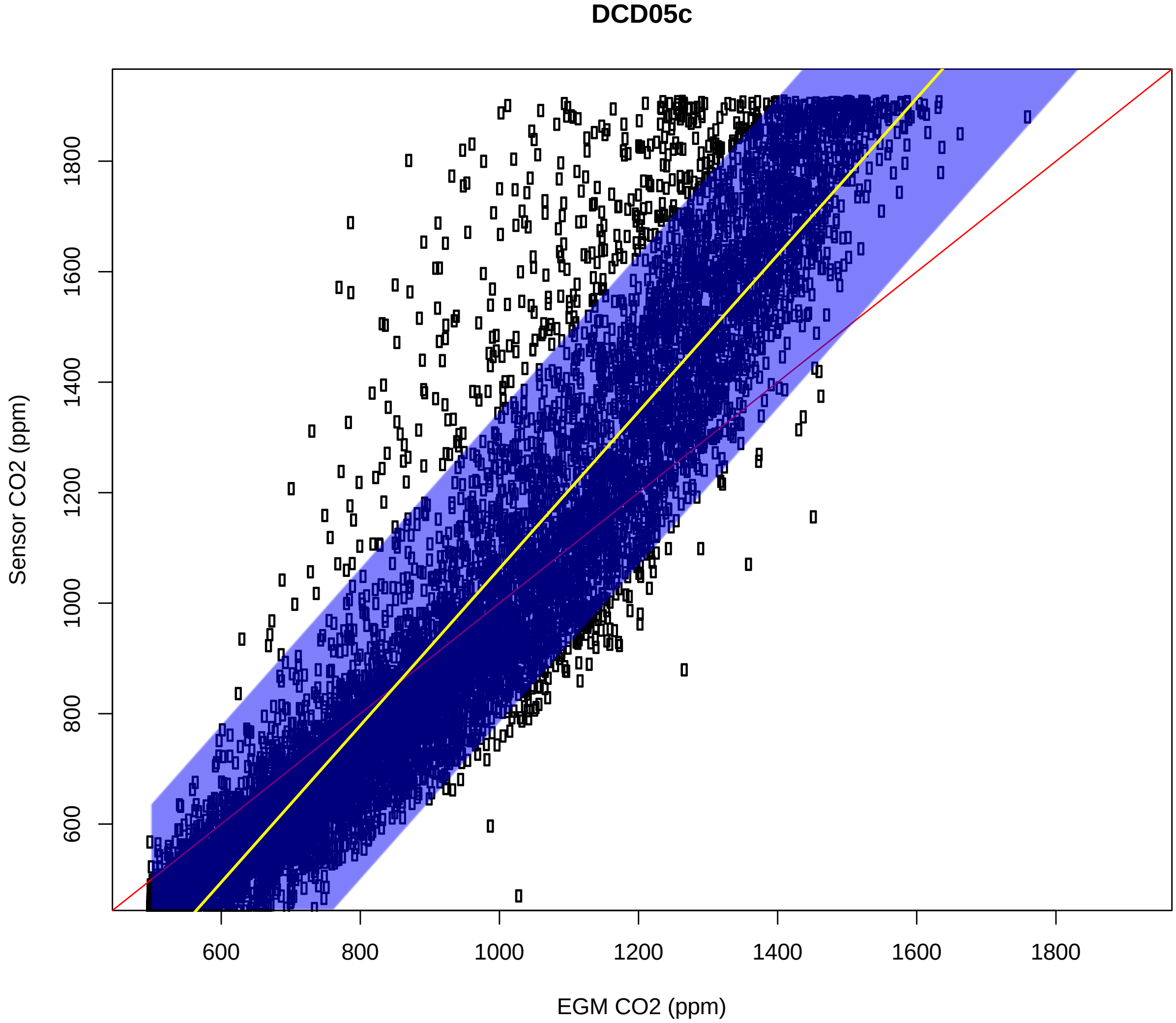
Source: Lawrence Berkeley National Laboratory

Figure C-3 (continued): Carbon Dioxide Sensor DCD05 (Telaire 8200, a Set of 3 Replicates) Evaluated in a Classroom



Source: Lawrence Berkeley National Laboratory

Figure C-3 (continued): Carbon Dioxide Sensor DCD05 (Telaire 8200, a Set of 3 Replicates) Evaluated in a Classroom



Source: Lawrence Berkeley National Laboratory

Table C-8: Carbon Dioxide Sensor Measurement Zero Offsets (ppm) Estimated in an Office Space

	Apr-Jun 2015	Sep-Nov 2015	Dec-Mar 2016	Apr-Jun 2016	Sep-Nov 2016	Dec-Mar 2017
GMW86	-19	10	-15	-21	8	-17
GMW86	-12	20	-13	-17	10	-16
GMW86	2	30	-5	-13	19	-13
TR9294	41	4	35	35	51	31
TR9294	24	1	25	55	35	15
TR9294	38	4	45	37	37	-1
ACD05	78	54	94	77	89	107
ACD05	31	-34	26	-13	-10	-8
ACD05	52	5	52	25	27	16
DCD05	-5	-19	17	2	-12	-6
DCD05	-19	7	-4	37	33	10
DCD05	-44	9	-2	5	-26	-17
T8100	82	46	63	64	73	29
T8100	85	65	78	84	90	41
T8100	88	50	60	73	82	10
T8200	1	2	21	16	45	-9
T8200	25	NA*	61	-17	56	NA*
T8200	-20	13	-15	-50	2	-40
COZIR	127	34	139	153	77	69
COZIR	166	75	132	177	148	133
COZIR	241	87	131	149	132	120

*** Sensor reported too few data during this period to support estimates of zero offset and gain error.**

Source: Lawrence Berkeley National Laboratory

Table C-9: Carbon Dioxide Sensor Measurement Gain Errors (ppm) Estimated in an Office Space

	Apr-Jun 2015	Sep-Nov 2015	Dec-Mar 2016	Apr-Jun 2016	Sep-Nov 2016	Dec-Mar 2017
GMW86	-13	-71	-11	-12	-55	-11
GMW86	-10	-72	-2	-6	-45	1
GMW86	-38	-94	-21	-18	-64	-10
TR9294	-87	-17	-63	-64	-83	-48
TR9294	-68	-28	-59	-117	-72	-38
TR9294	-85	-21	-82	-74	-65	-0.3
ACD05	-157	-97	-209	-141	-155	-236
ACD05	-91	31	-82	-9	-0.5	-25
ACD05	-133	-46	-136	-77	-71	-76
DCD05	-69	-53	-117	-116	-81	-95
DCD05	127	56	101	21	8	53
DCD05	4	-92	-38	-81	-48	-57
T8100	-152	-86	-109	-112	-119	-55
T8100	-159	-112	-138	-139	-140	-73
T8100	-147	-78	-90	-107	-114	-2
T8200	-29	-73	-89	-113	-171	-79
T8200	-27	NA*	-151	6	-121	NA*
T8200	-35	-122	-63	-23	-120	-54
COZIR	-90	125	-108	-114	50	-1
COZIR	-172	24	-116	-143	-95	-136
COZIR	-269	57	-106	-74	-36	-104

*** Sensor reported too few data during this period to support estimates of zero offset and gain error. Reference CO_2 = 1,000 ppm.**

Source: Lawrence Berkeley National Laboratory

Table C-10: Carbon Dioxide Sensor Measurement Zero Offsets (ppm) Estimated in a Conference Room

	Apr-Jun 2015	Sep-Nov 2015	Dec-Mar 2016	Apr-Jun 2016	Sep-Nov 2016	Dec-Mar 2017
GMW86	-2	-11	-4	2	-12	8
GMW86	6	-4	10	21	-12	11
GMW86	-5	-14	-3	5	-19	1
TR9294	-10	-16	-28	-6	-2	-20
TR9294	-5	-11	-17	-3	-4	-8
TR9294	0	-8	-30	-1	-1	-6
ACD05	-30	-28	-48	-15	-21	-68
ACD05	41	23	25	42	38	23
ACD05	29	11	14	33	26	17
DCD05	39	14	29	39	12	11
DCD05	6	1	4	7	-15	-10
DCD05	27	-4	22	20	9	27
T8100	23	21	-14	17	14	12
T8100	23	18	-3	26	13	9
T8100	13	13	-17	12	1	-1
T8200	-35	-50	-52	-29	-52	-36
T8200	-7	-27	-13	6	-15	-19
T8200	-52	-80	-86	-63	-86	-76
COZIR	69	30	47	41	28	12
COZIR	58	35	32	65	42	23
COZIR	111	101	82	108	115	51

Source: Lawrence Berkeley National Laboratory

Table C-11: Carbon Dioxide Sensor Measurement Gain Errors (ppm) Estimated in a Conference Room

	Apr-Jun 2015	Sep-Nov 2015	Dec-Mar 2016	Apr-Jun 2016	Sep-Nov 2016	Dec-Mar 2017
GMW86	-37	-18	-30	-41	-19	-48
GMW86	-57	-43	-67	-85	-30	-64
GMW86	-37	-22	-43	-58	-19	-48
TR9294	-25	3	16	-29	-29	-3
TR9294	-27	5	-0.1	-25	-17	-18
TR9294	-52	-6	12	-35	-31	-38
ACD05	57	102	75	55	68	92
ACD05	-138	-90	-120	-139	-126	-115
ACD05	-108	-60	-93	-111	-94	-94
DCD05	-148	-124	-121	-154	-113	-109
DCD05	-119	-105	-84	-104	-74	-81
DCD05	-106	-84	-123	-129	-110	-109
T8100	-71	-42	-7	-52	-41	-49
T8100	-69	-43	-18	-65	-33	-29
T8100	-33	-10	22	-19	14	6
T8200	20	36	39	-13	19	-14
T8200	51	76	23	-25	20	10
T8200	53	72	60	23	47	29
COZIR	-23	131	44	112	103	119
COZIR	-12	94	52	26	70	78
COZIR	-110	36	-9	-4	3	25

Reference CO_2 = 1,000 ppm

Source: Lawrence Berkeley National Laboratory

Table C-12: Carbon Dioxide Sensor Measurement Zero Offsets (ppm) and Gain Errors Estimated in a Classroom

	Apr-Jun 2015	Sep-Nov 2015	Dec-Mar 2016	Apr-Jun 2016	Sep-Nov 2016	Dec-Mar 2017
GMW86	3	11	-11	-10	-2	-13
GMW86	2	4	-18	-15	-2	-16
GMW86	-18	-12	-36	-36	-28	-43
TR9294	-11	-9	-26	-10	5	-3
TR9294	-17	-7	-28	-12	-6	-9
TR9294	-19	-8	-26	-15	-7	-10
ACD05	46	58	26	54	45	29
ACD05	51	62	38	58	57	43
ACD05	40	52	30	52	49	32
DCD05	-2	7	-11	3	-8	-9
DCD05	-30	-26	-44	-47	-43	-31
DCD05	-329*	-304*	-401*	-351*	-352*	-382*
T8100	5	9	3	10	31	32
T8100	-26	-32	-45	-41	-11	-19
T8100	-40	-36	-54	-41	-17	-30
T8200	-32	-45	-40	-36	-34	-24
T8200	-24	-20	-58	-38	-26	-42
T8200	-23	-29	-53	-38	-24	-40
COZIR	59	95	6	53	50	21
COZIR	84	107	12	47	39	8
COZIR	88	94	1	24	28	8

*** Observed nonlinearity between CO_2 sensor response with respect to reference concentration, but found no obvious reason that may explain this abnormality case.**

Source: Lawrence Berkeley National Laboratory

Table C-13: Carbon Dioxide Sensor Measurement Gain Errors (ppm) Estimated in a Classroom

	Apr-Jun 2015	Sep-Nov 2015	Dec-Mar 2016	Apr-Jun 2016	Sep-Nov 2016	Dec-Mar 2017
GMW86	1	-26	-20	-38	-65	-66
GMW86	-7	-26	-22	-39	-61	-61
GMW86	8	-14	-10	-25	-48	-49
TR9294	-2	-4	0.3	-9	-17	-19
TR9294	10	-3	8.4	-4	0.1	-2
TR9294	19	8	13	5	8	5
ACD05	-120	-131	-120	-121	-124	-132
ACD05	-136	-150	-142	-139	-146	-149
ACD05	-105	-121	-117	-113	-118	-118
DCD05	-47	-51	-28	-39	-59	-38
DCD05	-8	-18	10	10	-23	-5
DCD05	391*	371*	497*	369*	382*	458*
T8100	76	77	75	79	68	63
T8100	174	175	180	186	171	166
T8100	135	135	140	143	130	128
T8200	-48	-59	-61	-73	-76	-82
T8200	-42	-63	-28	-53	-61	-43
T8200	-5	-16	7	-15	-26	-9
COZIR	-32	-25	8	22	9	-10
COZIR	-93	-18	11	40	20	10
COZIR	-105	-28	8	40	17	9

*** Observed nonlinearity between CO_2 sensor response with respect to reference concentration, but found no obvious reason that may explain this abnormality case. Reference CO_2 = 1,000 ppm.**

Source: Lawrence Berkeley National Laboratory

APPENDIX D: People Counting for Ventilation Rate Control

Operating Principles of Occupant Counting

The recent review by Labeodan, Zeiler et al. (2015) summarizes common systems used in buildings for occupancy detection and counting. Several common approaches are summarized below.

Passive infrared (PIR) detectors detect infrared (IR) radiation from a warm object such as a person. PIR detectors are very widely used to sense occupancy and turn lights on and off. But the standard PIR systems used for control of lighting will not distinguish between one and multiple occupants. Brooks, Goyal et al. (2014) and Duarte, Van den Wymelenberg et al. (2013) demonstrated using PIR in small offices to detect the presence or absence of occupants. Assuming that small offices were occupied at their designed capacity, the studies used the resulted occupancy estimates to control building HVAC. However, this approach does not work for large open spaces and in spaces where the actual occupancy often differs from the design values, e.g., conference rooms. In a research study, Yun and Lee (2014) showed that two or more PIR detectors sensitive to IR from a restricted spatial zone could be used to detect people moving through a region of space, such as a doorway. The main advantages of PIR systems are the low cost of PIR detectors and the absence of privacy concerns. Disadvantages include an inability to distinguish people from other sources of infrared (IR) radiation and to distinguish single from multiple people.

Infrared beam systems employ multiple IR light beams and detectors that can sense the interruption of the light beam as a person moves across the beam. Some systems employ IR sources and detectors at the opposite sides of a doorway, while other systems maintain the IR sources and sensors in the same housing and rely on reflected IR light. Dedesko, Stephens et al. (2015) combined non-directional doorway beam-break sensors and CO_2 concentrations measured in patient rooms to estimate occupancy. There are several variations on the basic IR beam approach. The use of multiple parallel beams and the timing of beam interruption can determine the direction of a person's movement. IR beam systems tend to be lower cost than camera based systems and do not have privacy concerns. However, they have troubles distinguishing between a single person and multiple persons.

Infrared camera systems record and analyze the IR images from people as they pass through a spatial zone. They are capable of detecting and counting people in an open space, aside from counting people flow through a doorway. With suitable software, IR camera systems mounted on ceilings can count people and determine their direction of movement even when multiple individuals pass through the zone simultaneously. Thus, IR camera systems (and visible light camera systems, discussed subsequently) are well suited for use at wide entrances to buildings or rooms through which multiple people may simultaneously pass. They are more expensive than PIR and IR beam systems, but do not raise privacy concerns since identities of individuals cannot be determined from the IR images.

Visible light camera systems are similar to IR camera based systems but use visible light images together with software. Some counting technologies are software packages that connect to commonly used security cameras. For example, Liu, Guan et al. (2013) described methods used to estimate occupancy from a network of security cameras in an experimental workspace. These systems raise privacy concerns, but not necessarily exceeding the concerns associated with security cameras. Also, images can be blurred to ease privacy concerns. Cameras can be combined with other technologies to estimate occupancy. For example, Erickson, Achleitner et al. (2013) used a network of visual cameras in hallways and a network of PIR sensors in rooms to control HVAC operations in an office building.

Radio frequency identification (RFID) systems detect radio signals from RFID tags which can be carried by people. Passive RFID tags detect the radio signal for the RFID reader and send a response, but the tags have no power source. Many employees carry employee badges with RFID tags that are used to access buildings or rooms and RFID systems are routinely used to track inventory and movement of goods. Many common RFID systems require the RFID tag to be within about 10 cm from the reader, but high frequency RFID devices can have a range exceeding 10 m. Studies by Li, Calis et al. (2012) and Ni, Liu et al. (2004) used active RFID, which has a longer signal range up to 100 m, to determine occupancy and where people are located in buildings. There are privacy concerns associated with the use of RFID tags, since the tags generally indicate individual identity. Also, while these systems are useful to count employees with RFID tags, visitors without RFID tags will not be counted.

There are various mechanical systems that can be employed to count people entering and exiting spaces such as turn styles and door-swing sensors. An example of a mechanical system is a pressure sensitive floor mat containing large numbers of piezo-electric pressure sensors. A recently developed product[14] with 650 sensors per square meter can determine direction of travel, communicates wirelessly, and distinguished between a single and multiple moving persons. The mat width can be sufficient to count people flow through a broad entrance to a building through which many people may simultaneously walk. These systems do not raise privacy concerns.

People counts can be also estimated by tracking the number of wireless devices that send Wi-Fi signals to the local Wi-Fi network. Challenges of this method include people having multiple Wi-Fi devices, detection of Wi-Fi devices from outside of the building,

14 Instant Counting product (http://www.instantcounting.com).

and privacy concerns. However, counting system costs are potentially low for buildings with existing Wi-Fi networks. For example, Christensen, Melfi et al. (2014) monitored IP and MAC addresses in Wi-Fi access points and in routers, and correlated these addresses to the occupancy in an office building. Their approach makes use of existing network infrastructure, and does not require sensors be installed which would incur installation and maintenance costs. In addition, their approach has the advantage of potentially providing information on identity, location, or occupant movement. However, this technology requires further development to overcome two challenges: overlap coverage of signals and inconsistent Wi-Fi connectivity of mobile devices. Occupancy estimates from this approach may be sufficiently accurate for HVAC control, but the authors noted that this remains a question to be answer in future work.

Error accumulation is an important consideration for systems that determine the number of occupants from a count of occupants entering a space minus a count of occupants exiting a space. Small percentage errors can add up over time to large errors in the number of occupants. Thus, these counting systems are best suited to spaces that have known periods of no occupancy during which the occupant count can be reset to zero. In many buildings, this condition occurs at night when the spaces are unoccupied or have very few occupants.

Test Results

Table D-1 shows environmental conditions measured using Onset U12-012 temperature/relative humidity/light intensity data loggers during the evaluation tests. Lighting in the conference room was dimmed during presentations for some of the test periods. The building entrance had variable lighting conditions as a result of changing natural light from outside. The entrance under the view of the IR camera was not exposed to direct sunlight at any time during this study.

Results of the scripted tests involving only one person are summarized in **Error! Reference source not found.** and **Error! Reference source not found.**. Results of the scripted test involving two or more people are summarized in **Error! Reference source not found.** and **Error! Reference source not found.**.

Error! Reference source not found. and **Error! Reference source not found.** show the comparison between people counts recorded by the two technologies and by the observer when occupants unaware of the counting systems pass through the doorway at the two test locations.

Table D-1: Environmental Conditions Measured During Testing of People Counting at a Conference Room

Test	Date	Time	Avg. Air Temp. (ºC, ºF) Room	Avg. Air Temp. (ºC, ºF) Hallway	Avg. Relative Humidity (%) Room	Avg. Relative Humidity (%) Hallway	Avg. Light Intensity (lux) Room	Avg. Light Intensity (lux) Hallway
1	6/20	12:00 – 12:50	26, 78	25, 77	45	44	126	-
2	6/21	12:00 – 12:55	23, 74	24, 76	47	47	107	-
3	6/22	13:40 – 14:45	24, 75	24, 75	48	46	53	71
4	6/23	11:55 – 12:50	23, 74	23, 73	49	49	52	111
5	6/28	11:20 – 13:10	23, 74	23, 73	52	52	43	119
6	6/29	11:50 – 13:10	21, 70	21, 70	53	53	44	109
7	6/30	11:30 – 13:10	22, 72	22, 72	54	51	38	109
8	7/7	11:20 – 13:10	21, 70	21, 70	58	54	59	123

Source: Lawrence Berkeley National Laboratory

Table D-2: Environmental Conditions Measured During Testing of People Counting at a Building Entrance

Test	Date	Time	Avg. Air Temperature (ºC, ºF) Indoor	Avg. Air Temperature (ºC, ºF) Outdoor	Avg. Relative Humidity (%) Indoor	Avg. Relative Humidity (%) Outdoor	Avg. Light Intensity (lux) Indoor	Avg. Light Intensity (lux) Outdoor
1	7/28	12:55 – 14:25	22, 71	21, 69	57	61	88	1253
2	8/2	7:30 – 9:00	19, 66	14, 58	64	77	24	528
3	8/2	9:00 – 10:45	19, 66	14, 58	65	81	67	1375
4	8/2	10:45 – 12:25	19, 66	16, 60	65	78	120	1260
5	8/2	12:25 – 13:55	19, 67	17, 62	65	75	92	1191
6	8/4	8:05 – 9:50	19, 66	15, 59	64	77	105	1065
7	8/4	9:50 – 11:40	19, 66	16, 61	65	77	125	1250
8	8/4	11:40 – 13:30	19, 67	17, 62	65	75	99	1222

Source: Lawrence Berkeley National Laboratory

Table D-3: Scripted Test Results of People Counting at Conference Room

Test (one person)	N	N IR Cam. In	N IR Cam. Out	% Error IR Cam. In	% Error IR Cam. Out	N IR Beam In	N IR Beam Out	% Error IR Beam In	% Error IR Beam Out
Walking normal pace	3	3	4	0%	8%	3	3	0%	0%
Walking normal pace	10	10	10	0%	8%	10	10		
Walking fast pace	3	2	3	-8%	0%	1	2	-15%	-8%
Walking fast pace	10	10	10	-8%	0%	10	10		
Wearing cold winter coat	3	3	3	-17%	0%	3	3	17%	0%
Wearing cold winter coat	3	2	3	-17%	0%	4	3		
Wearing room temp winter coat	3	4	6	17%	50%	3	3	0%	0%
Wearing room temp winter coat	3	3	3	17%	50%	3	3		
Holding coffee (covered)	3	3	3	0%	0%	3	3	0%	0%
Holding coffee (covered)	3	3	3	0%	0%	3	3		
Holding coffee (uncovered)	3	3	3	0%	0%	3	3	0%	0%
Holding coffee (uncovered)	3	3	3	0%	0%	3	3		
Carrying warm laptop	3	3	3	0%	0%	2	3	-17%	0%
Carrying warm laptop	3	3	3	0%	0%	3	3		

Source: Lawrence Berkeley National Laboratory

Table D-4: Scripted Test Results of People Counting at a Building Entrance

Test (one person)	N	N IR Cam. In	N IR Cam. Out	% Error IR Cam. In	% Error IR Cam. Out	N IR Beam In	N IR Beam Out	% Error IR Beam In	% Error IR Beam Out
Walking at a normal pace	10	10	10	0%	5%	12	10	45%	0%
Walking at a normal pace	10	10	11	0%	5%	17	10	45%	0%
Walking at a fast pace	10	10	10	0%	0%	10	11	0%	5%
Walking at a fast pace	10	10	10	0%	0%	10	10	0%	5%
Wearing a cold winter coat	10	10	13	5%	15%	10	10	-5%	5%
Wearing a cold winter coat	10	11	10	5%	15%	9	11	-5%	5%
Wearing room temp winter coat	10	10	12	0%	15%	10	10	0%	0%
Wearing room temp winter coat	10	10	11	0%	15%	10	10	0%	0%
Holding covered cup of coffee	10	10	10	0%	5%	14	12	15%	5%
Holding covered cup of coffee	10	10	11	0%	5%	9	9	15%	5%
Holding uncov-ered coffee	10	10	10	0%	0%	13	10	25%	-10%
Holding uncov-ered coffee	10	10	10	0%	0%	12	8	25%	-10%
Carrying a warm laptop 1 person	10	10	12	0%	10%	7	10	-5%	-5%
Carrying a warm laptop 1 person	10	10	10	0%	10%	12	9	-5%	-5%

Source: Lawrence Berkeley National Laboratory

Table D-5: Scripted Test Results of People Counting at a Conference Room Involving Two or More People

Test	N	N IR Cam. In	N IR Cam. Out	% Error IR Cam. In	% Error IR Cam. Out	N IR Beam In	N IR Beam Out	% Error IR Beam In	% Error IR Beam Out
2 people walking one after another	20	20	20	-5%	0%	22	20	5%	-5%
2 people walking one after another	20	18	20	-5%	0%	20	18	5%	-5%
3 people walking one after another	30	28	33	-27%	5%	29	29	-7%	-3%
3 people walking one after another	30	16	30	-27%	5%	27	29	-7%	-3%
4 people walking one after another	40	40	38	-15%	-3%	33	40	-9%	-1%
4 people walking one after another	40	28	40	-15%	-3%	40	39	-9%	-1%
1 person entering while another person exits	10	10	10	-5%	-5%	3	6	-50%	-45%
1 person entering while another person exits	10	9	9	-5%	-5%	7	5	-50%	-45%
2 people enter while 2 other people exit	40	39	27	-3%	-33%	12	20	-70%	-50%
3 people entering while 2 other people exit	50	47	32	-6%	-36%	23	20	-54%	-60%
2 people walking side by side	40	24	29	-40%	-28%	15	20	-63%	-50%

Source: Lawrence Berkeley National Laboratory

Table D-6: Scripted Test Results of People Counting at a Building Entrance Involving Two More People

Test	N	N IR Cam. In	N IR Cam. Out	% Error IR Cam. In	% Error IR Cam. Out	N IR Beam In	N IR Beam Out	% Error IR Beam In	% Error IR Beam Out
2 people walking one after another	20	20	21	-3%	5%	20	19	0%	-3%
2 people walking one after another	20	19	21			20	20	0%	-3%
3 people walking one after another	30	28	31	-8%	5%	31	28	8%	-5%
3 people walking one after another	30	27	32			34	29	8%	-5%
4 people walking one after another	40	39	41	-1%	8%	37	36	-4%	-9%
4 people walking one after another	40	40	45			40	37	-4%	-9%
1 person entering while another person exits	10	10	10	0%	0%	8	10	-35%	0%
1 person entering while another person exits	10	10	10			5	10	-35%	0%
2 people enter while 2 other people exit	20	20	19	2%	-3%	10	15	-60%	-18%
2 people enter while 2 other people exit	20	21	20			6	18	-60%	-18%
3 people entering while 2 other people exit	25	30	32	22%	26%	15	23	-40%	-8%
3 people entering while 2 other people exit	25	31	31			15	23	-40%	-8%
2 people walking side by side	20	20	20	0%	0%	10	10	-50%	-50%
2 people walking side by side	20	20	20			10	10	-50%	-50%

Source: Lawrence Berkeley National Laboratory

Table D-7: Results of People Counts Evaluated at a Conference Room

	N (Observed Occupancy) In	N (Observed Occupancy) Out	N (IR Cam.) In	N (IR Cam.) Out	% Error (IR Cam.) In	% Error (IR Cam.) Out	N (IR Beam) In	N (IR Beam) Out	% Error (IR Beam) In	% Error (IR Beam) Out
1	47	38	48	43	2%	13%	43	33	-9%	-13%
2	28	26	23	24	-18%	-8%	24	18	-14%	-31%
3	60	50	63	77	5%	54%	46	49	-23%	-2%
4	22	14	24	12	9%	-14%	21	9	-5%	-36%
5	33	28	34	30	3%	7%	31	27	-6%	-4%
6	17	17	20	16	18%	-6%	15	11	-12%	-35%
7	47	39	43	38	-9%	-3%	48	35	2%	-10%
8	53	44	68	42	28%	-5%	53	46	0%	5%

Table D-8: Mean Percent Error and Range for IR Camera and IR Beam in Conference Room

	% Error (IR Cam.) In	% Error (IR Cam.) Out	% Error (IR Beam) In	% Error (IR Beam) Out
Mean	5%	5%	-8%	-16%
Range	-18% to 28%	-14% to 54%	-23% to 2%	-36% to 5%

Source: Lawrence Berkeley National Laboratory

Table D-9: Results of People Counts Evaluated at a Building Entrance

Test	N (Observed) In	N (Observed) Out	N IR Cam. In	N IR Cam. Out	% Error IR Cam. In	% Error IR Cam. Out	N IR Beam In	N IR Beam Out	% Error IR Beam In	% Error IR Beam Out
1	31	36	39	48	26%	33%	27	34	-13%	-6%
2	15	3	19	4	27%	33%	18	2	20%	-33%
3	47	22	47	20	0%	-9%	44	17	-6%	-23%
4	36	29	40	40	11%	38%	40	29	11%	0%
5	29	37	34	57	17%	54%	31	37	7%	0%
6	50	11	26	7	-48%	-36%	21	4	-58%	-64%
7	49	43	40	21	-18%	-51%	36	14	-27%	-67%
8	27	43	46	31	70%	-28%	35	27	30%	-37%

Source: Lawrence Berkeley National Laboratory

Table D-10: Mean Percent Error and Range for IR Camera and IR Beam at Building Entrance

	% Error (IR Cam.) In	% Error (IR Cam.) Out	% Error (IR Beam) In	% Error (IR Beam) Out
Mean	11%	4%	-5%	-29%
Range	-48% to 70%	-51% to 54%	-58% to 30%	-67% to 0%

Source: Lawrence Berkeley National Laboratory

APPENDIX E: Transient Method for Calculating Ventilation Rates

Ventilation Rates Measured Using Carbon Dioxide Decay Method

Ventilation rates were measured in the two office spaces using CO_2 decay method. Figure E-1 and Figure E-2 show the floor plan of the two spaces. The two spaces were unoccupied on the two Saturdays, April 1and 8, 2017, when ventilation rates were measured. LBNL facilities modified the HVAC operation schedule in energy management system (EMS) so that the rooftop units serving study space 1, and the wall-mount units serving study space 2, ran on weekday schedule when ventilation rates were measured. Both office spaces are part of LBNL facility.

Very different weather conditions were encountered on the two days when ventilation rates were measured. The first Saturday was a warmer day with milder wind. The average outdoor air temperature measured by LBNL onsite meteorological tower between 9 am and 3 pm (during when measurements were made) was 19 ^{o}C (67 ^{o}F). The average wind speed was (4 m/s 9 mph). The second Saturday was cooler [8 ^{o}C (47 ^{o}F) average outdoor air temperature] and windier [9 m/s (20 mph) average wind speed].

CO_2 was released from a compressed gas cylinder directly into the occupy space and allowed to mix. Concentrations were monitored by a calibrated EGM-4 gas analyzer (PP Systems) in a central location. Ventilation rate was determined using linear regression from a portion of the CO_2 decay curve that is well described by this equation:

$$CO_2(t) = CO_{2,out} + CO_2(t_0)\ exp[-k(t-t_0)]$$

where $CO_{2,out}$ is the outdoor CO_2 concentrations, $CO_2(t_0)$ is the initial indoor CO_2 concentration at the start of the decay curve, and k (h^{-1}) is the ventilation rate being determined.

On each of the two test days, the CO_2 decay test was performed once in the morning (around 10 and 11 am) and repeated again in the early afternoon (around 1 and 2 pm). Table E-1 shows that ventilation rates in both study spaces were approximately 1.6 h^{-1}.

Carbon Dioxide Concentrations Measured in Two Study Spaces

Figure E-1and Figure E-2 show the floor plan of the two office spaces where people counts and CO_2 concentrations were measured. In the larger office space 1 (Figure E-1), CO_2 concentrations were monitored using EGM4 gas analyzer at a central location, and also at 7 additional locations using Vaisala GMW94 that were newly purchased and calibrated by manufacturer. The reported accuracy of this CO_2 sensor is ± 30 ppm or 2 percent of reading when temperature is between 20 and 30°C. Product literature[15] claimed total accuracy at room temperature is within ± 75 ppm at 600 and 1,000 ppm for 5 years.

Table E-1: Results From Carbon Dioxide Decay Tests

Test Date	Decay Test	Office Space 1 k (h^{-1}) (Std. Error)	Office Space 1 R^2	Office Space 2 k (h^{-1}) (Std. Error)	Office Space 2 R^2
4/1/2017	Test 1	-1.62 (0.004)	0.999	-1.66 (0.002)	1.000
4/1/2017	Test 2	-1.67 (0.014)	0.995	-1.61 (0.002)	1.000
4/8/2017	Test 1	-1.56 (0.007)	0.998	-1.57 (0.004)	1.000
4/8/2017	Test 2	-1.63 (0.019)	0.992	-1.58 (0.003)	1.000

Source: Lawrence Berkeley National Laboratory

CO_2 concentrations in the smaller office space 2 (Figure E-2) were monitored using two Vaisala GMW94 at two locations: central hallway and inside a private office. The difference in CO_2 concentrations measured at different locations in the two study spaces with respect to the central location are shown in Table E-2 and Table E-3.

15 https://www.vaisala.com/sites/default/files/documents/GMW90%20Series%20User's%20Guide%20in%20English%20M211659EN.pdf.

Table E-2: Difference in Carbon Dioxide Concentrations Measured at Different Locations, With Respect To Concentrations Measured at the Central Location in Office Test Space 1

	Mean Diff.	Std Dev. Diff	Mean abs(Diff.)	Std Dev. Abs(Diff.)	Range (95%)	% Time ± 30 ppm	% Time ± 75 ppm
Hallway E1	-4	12	9	9	-28 – 13	97%	100%
Hallway E2	11	9	12	8	-6 – 30	97%	100%
Hallway W1	9	13	14	9	-18 – 31	97%	100%
Hallway W2	-22	12	23	12	-48 – 0	76%	100%
Conf Room 1	45	76	49	73	-29 – 313	63%	83%
Conf Room 2	-36	26	41	18	-74 – 38	26%	97%
Conf Room 3	-28	24	33	16	-58 – 40	45%	98%

Source: Lawrence Berkeley National Laboratory

Table E-3: Difference in Carbon Dioxide Concentrations Measured in a Private Office (Room 123), With Respect To Concentrations Measured at the Central Location in Office Test Space 2

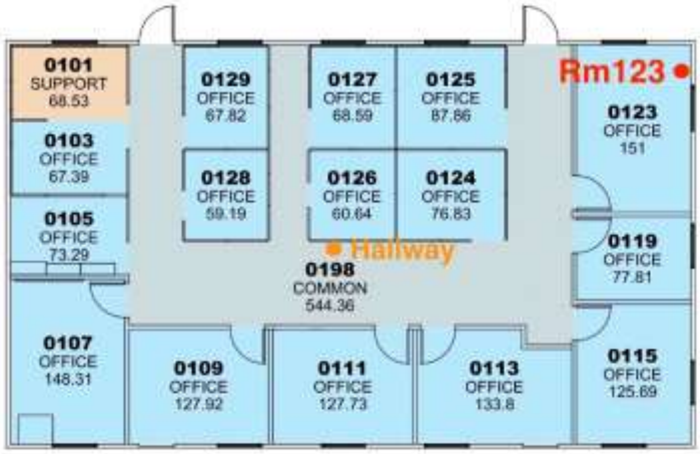
	Mean Diff.	Std Dev. Diff	Mean abs(Diff.)	Std Dev. Abs(Diff.)	Range (95%)	% Time ± 30 ppm	% Time ± 75 ppm
Room 123	37	33	37	33	1 – 124	59%	89%

Source: Lawrence Berkeley National Laboratory

Figure E-1: Floor Plan of Office Test Space 1

Source: Lawrence Berkeley National Laboratory

Figure E-2: Floor Plan of Office Test Space 2



Room Category	Room Area	Room Count
COMMON	544	1
OFFICE	1,454	15
SUPPORT	69	1
TOTAL	2,067	17

Source: Lawrence Berkeley National Laboratory

Figure E-3: Measured Carbon Dioxide and People Counts in Office Test Space 1

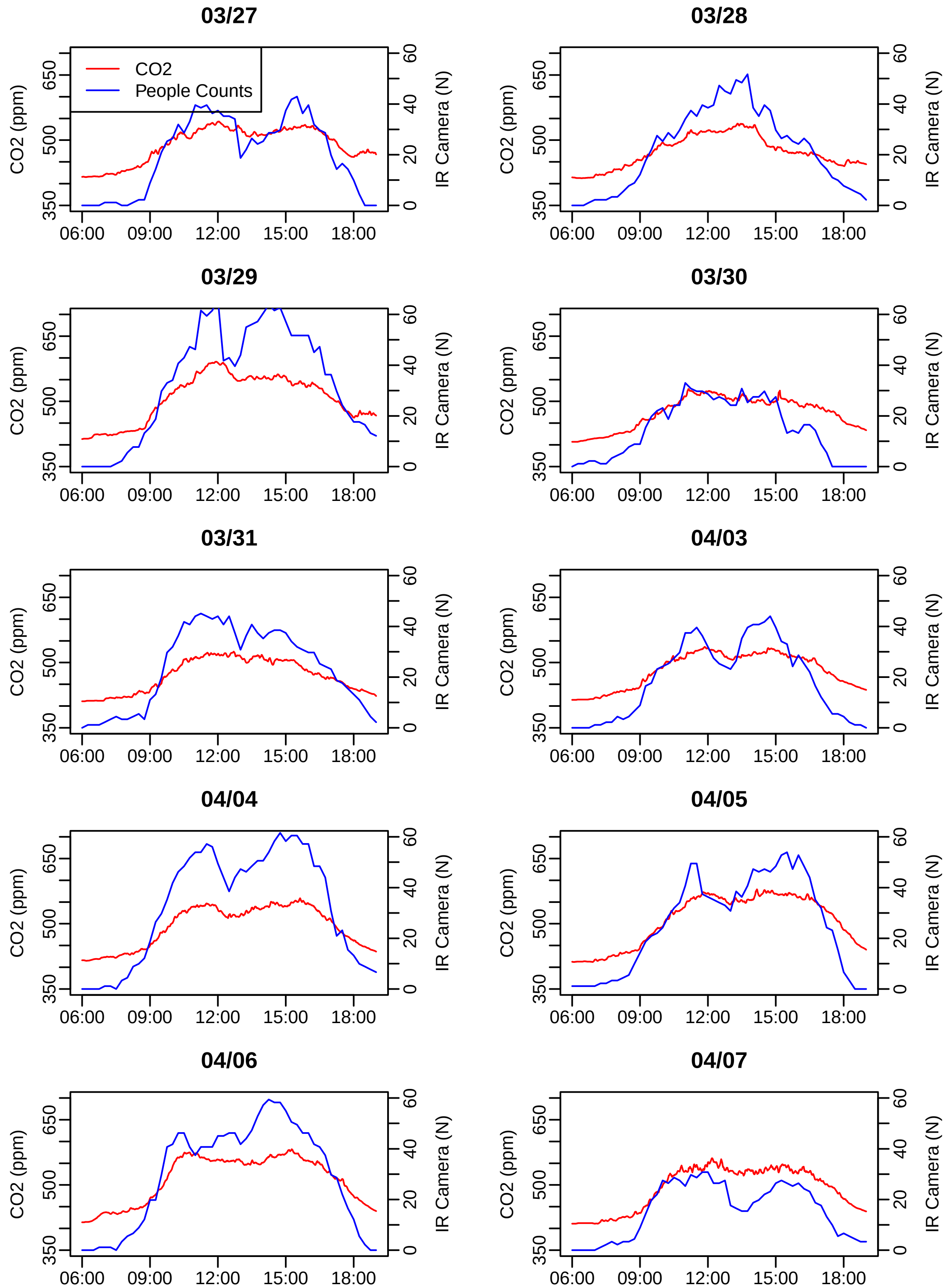
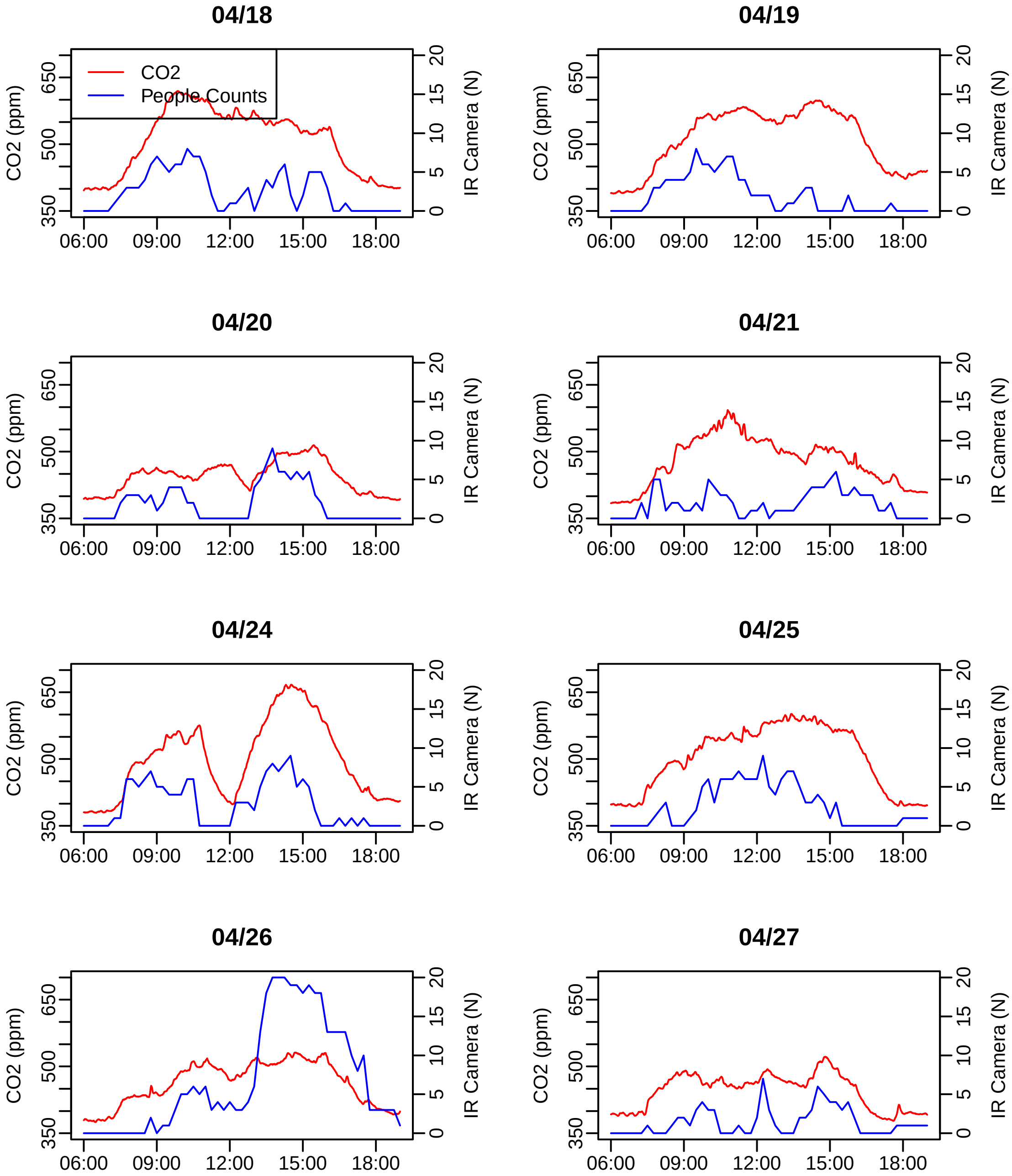


Figure E-4: Measured Carbon Dioxide and People Counts in Office Test Space 2



Source: Lawrence Berkeley National Laboratory