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DEMAND-CONTROLLED VENTILATION AND CLASSROOM VENTILATION

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PREFACE

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ABSTRACT

This document summarizes research on demand-controlled ventilation and classroom ventilation, including field studies and building energy computer modeling. The research on classroom ventilation collected data on California elementary school classrooms over a two-year period to investigate associations between ventilation rates and student illness-related absences. Major findings included:

- The single-location carbon dioxide sensors widely used for demand-controlled ventilation frequently fail to effectively control ventilation rates.
- Multilocation carbon dioxide measurement systems with more expensive sensors connected to multilocation sampling systems may measure carbon dioxide more accurately.
- Currently available systems that visually count occupants work well but have large counting errors in some situations.
- In meeting rooms, carbon dioxide measurements at return-air grilles appear to be more accurate than wall-mounted sensors.
- In California, demand-controlled ventilation in general office spaces is projected to save significant energy and be cost-effective only if typical ventilation rates without demand-controlled ventilation are very high relative to building code ventilation rates.

Several recommendations were developed for demand-controlled ventilation specifications in the California Title 24 Building Energy Efficiency Standards. Other findings included:

- Median classroom ventilation rates were below the California guideline and 40 percent lower in portable buildings than in permanent buildings.
- Overall, one additional liter per second per person of ventilation rate was associated with 1.6 percent fewer illness absences.
- Increasing average ventilation rates in California K-12 classrooms from the current average to the required level is estimated to decrease illness absences by 3.4 percent, increasing state attendance-based funding to school districts by $33 million, with an additional $6.2 million in increased energy costs. Further ventilation rate increases could provide additional benefits.
- Intervention studies are recommended to confirm these findings.
- Energy costs of heating/cooling unoccupied classrooms statewide are modest, but a large portion occurs in relatively few classrooms.

Keywords: Absence, buildings, carbon dioxide, demand-controlled ventilation, energy, indoor air quality, schools, ventilation

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EXECUTIVE SUMMARY

Introduction

This project focused on building ventilation. Ventilation, the supply of outdoor air to a building, is necessary to control indoor-generated air pollutant concentrations. From an energy efficiency perspective, the amount of ventilation during hot and cold weather should be minimized because ventilation air must often be heated, cooled, or dehumidified. Prior ventilation research has shown that occupants are typically more satisfied with air quality, have fewer adverse health symptoms, slightly higher levels of work performance, and lower absence rates in offices and schools with higher ventilation rates; however, formalized data supporting this observation is sparse. About 9 percent of energy used in U.S. commercial buildings is attributable to heating and cooling ventilation air supplied mechanically with fans and through uncontrolled air infiltration (leakage) through the building envelope. No comparable estimates are available for California's commercial buildings, but the fraction of total building energy attributable to ventilation is likely to be comparable or moderately smaller in California.

Given the ventilation impacts on buildings, ventilation selection methods and rates must strike a balance between indoor environmental quality, energy consumption, and occupant performance. Minimum ventilation standards have been established that specify minimum design ventilation rates for various building types. In California, these minimum ventilation rates are specified in the *2008 California Building Energy Efficiency Standards* and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) ventilation standards. Due to a lack of data, the scientific foundation for current minimum ventilation standards is relatively weak, particularly for buildings other than offices. There is a clear need for scientifically-based minimum ventilation standards.

This research project focused on a technology for controlling ventilation rates called demand-controlled ventilation. Demand-controlled ventilation systems adjust ventilation rates based on indoor carbon dioxide (CO_2) levels to maintain safe indoor air quality as deemed acceptable by industry standards (ASHRAE 62) or government regulations. The project also focused on improving both data and knowledge related to minimum ventilation requirements in classrooms.

Project Purpose

This research was performed to provide information for revisions to the California Building Energy Efficiency Standards and also to help building designers and operators make better decisions pertaining to demand-controlled ventilation and classroom ventilation.

Project Results

CO_2 sensors are often installed in commercial buildings to obtain CO_2-level data. The sensor information is used in demand-controlled ventilation, which automatically adjusts outdoor air ventilation rates based on the CO_2 levels within the building. Reasonably accurate CO_2 measurements are necessary for successful demand-controlled ventilation. Prior research has suggested that substantial measurement errors exist with CO_2 sensor measurements. This study evaluated: (a) the accuracy of 208 CO_2 single-location sensors in 34 commercial buildings, b) the accuracy of four multilocation CO_2 measurement systems that use tubing, valves, and pumps to measure multiple locations with single CO_2 sensors, and c) the spatial variability of CO_2 concentrations within meeting rooms.

Field studies evaluated the accuracy of single-location CO_2 sensors, including multiple calibration checks for concentrations of 90 sensors. Sensor accuracy was checked at multiple CO_2 concentrations using primary standard calibration gases. From these evaluations, average errors were small, 26 parts per million (ppm) of CO_2 at 760 ppm and 9 ppm at 1,010 ppm. However, the average errors were 118 ppm (16 percent) and 138 ppm (14 percent) at concentrations of 760 and 1,010 ppm, respectively. The *2008 California Building Energy Efficiency Standards* specify that sensor error must be certified as no greater than 75 ppm for a period of five years after sensor installation. At 1,010 ppm, 40 percent of sensors had errors greater than ±75 ppm and 31 percent of sensors had errors greater than ±100 ppm. At 760 ppm, 47 percent of sensors had errors greater than ±75 ppm and 37 percent of sensors had errors greater than ±100 ppm. A significant fraction of sensors had errors substantially larger than 100 ppm. For example, at 1,010 ppm, 19 percent of sensors had an error greater than 200 ppm, and 13 percent of sensors had errors greater than 300 ppm.

The field studies also included calibration checks at a single CO_2 concentration level for 118 sensors at the concentrations encountered in the buildings, which were normally less than 500 ppm during the testing. For analyses, these data were combined with data from the calibration challenges at 510 ppm obtained during the multiconcentration calibration checks. For the resulting data set, the average error was 60 ppm, and the average absolute value of error was 154 ppm.

The analyses indicated that there were statistically significant differences between the average sensor accuracies from different manufacturers. Sensors with a single–lamp, single-wavelength design tended to have a statistically significant smaller average error than sensors with other designs, except for single–lamp, dual-wavelength sensors, which did not have a statistically significant lower accuracy[1]. Sensor age was not consistently a statistically significant predictor of error.

Errors based on the CO_2 concentrations displayed by building energy management systems were generally very close to the errors determined from sensor displays (when available). The absolute value average of the difference between 113 paired estimates of error was 25 ppm; however, excluding data from two sensors located within the same building, the average difference was 10 ppm. These findings indicate that the substantial measurement errors found in this study are sensor errors, not errors in translating the sensor output signals to the energy management systems.

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[1] In this classification scheme, lamp refers to the infrared source(s) and wavelength refers to the wavelength(s) of infrared energy detected by the sensor's detector.

Laboratory-based evaluations of nine sensors with large measurement errors did not identify definite causes of sensor failures. The study determined that four of the nine sensors had an output signal that was essentially invariable with CO_2 concentration. For example, the sensors were nonfunctional and yet still deployed, which indicated that facility managers were not always aware of obviously faulty sensors. These findings suggest that sensor fault detection systems that provide alarms when sensors are clearly faulty may be beneficial for maintaining demand-controlled ventilation system performance.

The evaluations also identified slight soiling or corrosion of optical cells that detect occupancy level by monitoring the incoming and outgoing people. Also, holes in the fabrics through which CO_2 diffuses into optical cells of two sensors may possibly have contributed to performance degradations. In one of two cases, when the manufacturer's calibration protocol could be implemented, sensor accuracy was clearly improved after the protocol was implemented.

The Iowa Energy Center recently released the results from a laboratory-based study that tested 15 new single-location CO_2 sensor models for accuracy. Although its report does not provide summary statistics, its findings are broadly consistent with the field study findings of CO_2 sensor accuracy described in this report. Many of the new CO_2 sensors had errors greater than 75 ppm, which were not unusual.

The facility managers of 13 buildings provided data on the CO_2 set point concentration. The set point concentration is the allowable CO_2 limit for which the demand-controlled ventilation system increased the ventilation rate. The reported set point concentrations ranged from 500 ppm (in one instance) to 1,100 ppm. The building-weighted-average set point concentration was 860 ppm. When asked, no facility manager indicated that he or she had calibrated sensors since sensor installation.

A pilot study evaluated the accuracy of multilocation CO_2 measurement systems using data collected from systems installed in two buildings. The same manufacturer provided the multilocation measurement systems used in both buildings. In the first building, the average and standard deviation in error for the key CO_2 concentration ranges in the indoor minus outdoor CO_2 concentration difference were 14 ppm and 39 ppm, respectively, and in 16 of 18 cases the error was 36 ppm or smaller. In the second building, the measured CO_2 concentrations were consistently 110 ppm greater than the CO_2 concentration measured with the reference CO_2 instrument. Outdoor CO_2 concentrations measured by the building's measurement system averaged 510 ppm, which is about 110 ppm larger than the typical outdoor air CO_2 concentration. In both of these buildings, the error in the difference between indoor and outdoor CO_2 concentration, which is the appropriate control input for demand-controlled ventilation, was small except at a couple of measurement locations.

Multipoint measurements of CO_2 concentrations were taken in occupied meeting rooms to obtain information for selecting sensor installation locations. Data were analyzed for 30-minute to 90-minute periods of meeting room occupancy. The Title 24 standard requires that CO_2 be measured between 0.9 m and 1.8 m (3 feet and 6 feet) above the floor. The multipoint measurement results varied among the meeting rooms. In some instances, concentrations at different wall-mounted sample points varied by more than 200 ppm and concentrations at these locations sometimes fluctuated rapidly. These concentration differences may partly be a consequence of the high CO_2 concentrations (for example, 50,000 ppm) in the exhaled breath of nearby occupants. In four of seven data sets, the period-average CO_2 concentration at return grilles were within 5 percent of the period-average of all CO_2 concentration measurements made at locations on walls; for the other three data sets the deviations were 7, 11, and 16 percent. Return-air (air entering the space conditioning system return plenum) CO_2 concentrations were not consistently higher or lower than the average concentration at locations on walls. In four data sets, the average CO_2 concentration at the return-air location was between the lowest and highest average CO_2 concentrations measured at wall locations; while in the other three data sets, the average concentrations were lowest at the return grilles and highest at the wall locations. There was no consistent increase or decrease in CO_2 concentrations with height.

As an alternative to CO_2 sensors, devices that use optical methods to count people as they enter and exit a building or room could provide the control signal for demand-controlled ventilation. A pilot-scale study evaluated the counting accuracy of two people-counting systems, one a commercially available product and the second a prototype. The evaluations included controlled challenges of the people counting systems using preplanned occupant movements through doorways and evaluations of counting accuracies when occupants unaware of the counting systems passed through the entrance doors of the building or room. The two people-counting systems had high counting accuracies with errors typically less than 10 percent for typical nondemanding counting events. However, counting errors were high in some highly challenging situations, such as multiple people passing simultaneously through a door. Counting errors, for at least one system, were very high if people stood in the field of view of the sensor. Both counting systems have limitations and would need to be used only at appropriate sites and where the demanding situations that led to counting errors were rare.

Demand-controlled ventilation is most commonly used in spaces such as meeting rooms with high and variable occupancy. Another element of the research was modeling to assess the potential energy savings from use of demand-controlled ventilation in general office spaces. EnergyPlus, a robust modeling software, was used to simulate a prototypical office building that meets the *2008 California Building Energy Efficiency Standards* prescriptive requirements. These simulations calculated the demand-controlled ventilation energy savings potential in five typical California climates per three design occupancy densities and two minimum ventilation rates. The assumed minimum ventilation rates in offices without demand-controlled ventilation, based on two measurement methods employed in a large survey, were 38 and 13 liters/second (L/s) per occupant, respectively. The life-cycle cost analysis results showed demand-controlled ventilation was cost-effective for office spaces if the typical minimum ventilation rate without demand-controlled ventilation was 38 L/s per person, except at the low design occupancy of 10.8 people per 100 square meters (m^2) in California Climate Zones 3 (north coast, San Francisco Bay Area) and 6 (south coast, Los Angeles and Santa Barbara areas). Demand-controlled ventilation was not found to be cost-effective if the typical minimum ventilation rate without demand-controlled ventilation was 13 L/s per occupant, except at high design occupancy of 21.5 people per 100 m^2 in California Climate Zones 14 (desert) and 16 (mountains). Until the large uncertainties about the base-case ventilation rates in offices without demand-controlled ventilation are reduced, the case for requiring demand-controlled ventilation in general office spaces will be weak. With a 10.8 people per 100 m^2 office occupant density, demand-controlled ventilation became cost-effective when the base-case minimum ventilation rate was greater than 42.5, 43.0, 24.0, 19.0, and 18.0 L/s per person for California Climate Zones 3, 6, 12, 14, and 16, respectively.

The findings from the Iowa Energy Center laboratory studies and this project indicate that many CO_2-based demand-controlled ventilation systems will fail to meet the design energy savings goals while assuring that ventilation rates meet code requirements due to poor sensor accuracy. Given this finding, the researchers questioned whether or not the current prescriptions for demand-controlled ventilation in the *2008 California Building Energy Efficiency Standards* are adequate. Given the importance of ventilation and the energy savings potential of demand-controlled ventilation, further research and industry-led technology improvement activities are warranted. Some possible technical options for improving demand-controlled ventilation performance include:

- Sensor costs are likely to increase when single-location CO_2 sensor manufacturers for demand-controlled ventilation applications change technologies to improve CO_2 sensor accuracy. Users of CO_2 sensors for demand-controlled ventilation applications perform sensor calibrations immediately after initial sensor installation and periodically thereafter. Research is needed to determine if such calibration protocols would lead to acceptable accuracy and whether costs are acceptable.
- Demand-controlled ventilation systems employing existing CO_2 sensors that are more accurate, stable, and expensive than the sensors traditionally used for demand-controlled ventilation with sampling system options that take measurements at multiple locations.
- Demand-controlled ventilation systems using sensors that count occupants, as opposed to sensors that measure CO_2 concentrations.

With respect to selecting locations for CO_2 sensors in meeting rooms, this research did not result in definitive guidance; however, the results suggested that measurements at return-air grilles may be preferred to measurements at wall-mounted locations.

This research led to seven recommendations for modifications to the specifications for demand-controlled ventilation in the *2008 California Building Energy Efficiency Standards.* These recommendations include:

- CO_2 sensors installed in new demand-controlled ventilation installations should have air inlet ports and written protocols that make it possible to calibrate the deployed sensors using CO_2 calibration gas samples. The inlet ports must provide paths for introducing calibration gas samples into the sensors. The protocols must provide directions that a facility manager or building control system professional can use to check and, if necessary, adjust the sensors' calibration using at a minimum two calibration gas samples. The calibration protocol should specify that one calibration gas sample has a CO_2 concentration between 950 and 1,050 ppm, with the actual concentration of the calibration gas known within ± 2 percent. The protocol should specify calibration with a second calibration gas concentration of either zero ppm CO_2 or between 450 and 550 ppm CO_2, with the actual concentration of the calibration gas known within ± 2 percent. The inlet port and calibration protocol are not required if the sensor manufacturer or its agent maintains a sensor exchange program in which deployed sensors are replaced with new or used factory-calibrated sensors at least once per year.

- Within 60 days after installation in a building, all CO_2 sensors installed for demand-controlled ventilation should be calibrated, using the manufacturer's recommended protocol, to assure CO_2 measurements are accurate within ± 75 ppm. The protocol must check and, if necessary, adjust the sensor's calibration using, at a minimum, two calibration gas samples, one with a CO_2 concentration between 950 and 1,050 ppm and the second with a CO_2 concentration of either zero ppm or between 450 and 550 ppm. The concentration of the CO_2 in the calibration gases should be known within ± 2 percent. This calibration is not required if the sensor is provided with documentation demonstrating that a comparable calibration was implemented for the specific sensor within the past 90 days and that the sensor is accurate within ± 75 ppm at 500 ± 50 and 1,000 ± 50 ppm CO_2 concentrations when measured at sea level and 77°F (25°C).

- All CO_2 sensors should have a continuously readable visual display of the current CO_2 concentration. Manufacturers may provide a cover that makes the display accessible to facility managers, but not to other building occupants.

- Change the existing specification in Title 24 that reads "CO_2 sensors shall be located in the room between 3 ft. and 6 ft. (0.9 and 1.8 m) above the floor or at the anticipated height of the occupants heads" to "CO_2 sensors shall be located in the room between 3 ft. and 6 ft. (0.9 and 1.8 m) above the floor or at the anticipated height of the occupant's heads or in the return-air duct if the return-air duct contains only air from the room for which demand-controlled ventilation is implemented. Sensors shall not be installed in return air ducts if the room has a ventilation system designed to produce a displacement air flow pattern between the floor and the ceiling or if the ceiling is more than 14 ft. (4.3 m) above the floor. Sensors shall not be installed in return-air plenums or at the plane of the return-air grille."

- Change the existing specification in Title 24 that reads "For each system with demand-controlled ventilation, CO_2 sensors shall be installed in each room that meets the criteria of Section 121(c)3B with no less than one sensor per 10,000 ft^2 of floor space" by adding this text immediately following the preceding sentence: "In addition to stand-alone sensors that measure the CO_2 concentration at a single location, measurements may be performed with measurement systems that use tubing, valves, and pumps to measure at multiple indoor locations with a single CO_2 sensor if data is available from each location at least once every 10 minutes."

- The required building space types for which demand-controlled ventilation is required in Title 24 should not be expanded to include general office spaces. Demand-controlled ventilation should continue to be optional for general office spaces.

- Title 24's specifications pertaining to demand-controlled ventilation should not be modified to allow the use of optical people counting, in place of CO_2 sensors, to provide the control signal for demand-controlled ventilation.

The limited available evidence suggests that lower ventilation rates in both offices and schools are associated with increased illness absences. Data was collected on this relationship in California elementary schools.

Data sets during two school years between 2009-2011 on estimated ventilation rates and illness-related absences were collected from 162 classrooms in 28 schools, within three school districts with distinctly different climates: the South Coast, with mild winters and warm summers; the San Francisco Bay Area, with mild summers and winters; and the Central Valley, with cold winters and hot summers. Schools were selected within each district across a range of socioeconomic levels, and within schools, 3rd, 4th, and 5th grade classrooms were included in the study. Both permanent and portable building types were included while mixed grade and dedicated special education classrooms were excluded. Daily ventilation rates were estimated from real-time indoor CO_2 concentrations measured by internet-connected sensors in each classroom. School districts provided daily classroom-level absence data and periodic demographic data. Analyses included four summary metrics for ventilation rates, averaging ventilation rates over periods ranging from 3 days to 21 days, with a 7-day average the primary previously assumed metric. Relationships between daily illness absence and ventilation rate metrics were estimated separately by districts.

Analyses included data from 10 schools and 59 South Coast classrooms with no air-conditioning (AC) and mostly naturally ventilated classrooms; 5 schools and 26 Bay Area classrooms with multiple ventilation types; and 9 schools and 51 Central Valley classrooms, all with AC. Median daily ventilation rates in L/s per person were, by district, South Coast, 7.0; Bay Area, 5.1; and Central Valley, 2.6. Median daily ventilation rates in L/s per person by building type were, permanent classrooms, 6.8, and portable classrooms, 5.0; and by ventilation type, natural, 6.0, mechanical/no AC, 7.6, and with AC, 2.8. Mean daily classroom proportion of illness absence ranged from 2.1-2.5 across all districts. In adjusted models, for each additional 1 L/s per person of ventilation rate, illness absence was almost invariably lower: statistically significant in the South Coast (1.0-1.3 percent), statistically insignificant in the Bay Area (1.2-1.5 percent) and Central Valley (0.0-2.0 percent), and statistically significant when combined (1.4-1.8 percent).

All school districts had overall median daily ventilation rates below the Title 24 minimum ventilation rate standard of 7.1 L/s per person. Median ventilation rates were 40 percent lower in portable building than in permanent buildings and 54 percent lower in air-conditioned than naturally ventilated classrooms. Estimates in all districts showed consistent patterns, with relative decreases in illness absences for the seven-day averaged ventilation rate metric ranging across models from 1.0-1.6 percent per L/s per person. Strength of associations across models tended to increase as the averaging period for ventilation rates increased, rather than peaking for the seven-day metric as hypothesized. The number of available valid classroom days data for Bay Area and Central Valley districts was substantially lower (56 percent and 37 percent lower, respectively) than that for the South Coast, which may explain the lack of statistical significance despite similar point estimates. These estimates would apply within the ventilation rate range observed, roughly 1.4-20.3 L/s per person, mostly above the state guideline.

If these relationships were confirmed, an increase in average classroom ventilation rates from 4 to 7.1 L/s per person (from the average in overall California classrooms to the state guideline level) would be associated with at least a 3.4 percent decrease in illness absence relative to the current illness absence rate.

Project Benefits

Based on these findings and other available data, making this change in ventilation rates to all California K-12 schools would be associated with a $33 million increase to school districts in attendance-based state funding but only $4.0 million in increased energy costs to districts for ventilation, heating, and cooling. Thus the low ventilation rates excessively found in current classrooms that save energy may have unrecognized costs of increased health problems and related illness absence among students. Increasing ventilation rates above the recommended minimum levels, up to 20 L/s per person or higher, may further substantially decrease illness absence. If the magnitude of the relationships observed here and the costs and benefits estimates are confirmed, it would be advantageous to students, their families, and school districts. It is also highly cost-effective to ensure that ventilation rates in elementary school classrooms substantially exceed current recommended ventilation guidelines.

Among the approximately 6,224,000 students in 303,400 classrooms in 9,900 schools during 2009-10[2], an increase in ventilation rate from 4 L/s to 7.1 L/s per person would also produce benefits for families in decreased costs for caregiver time amounting to approximately $80 million. The caregiver time valuation includes substantial subjectivity and uncertainty, which requires further research. Including the $33 million in additional state funding to school districts, the total estimated benefits equal $113 million. Reductions in medical care costs for students, monetized improvements in quality of life for children and families, or any parallel costs related to sick leave for teachers and staff have not been estimated.

[2] http://www.cde.ca.gov/ls/fa/sf/facts.asp

CHAPTER 1: Introduction

The term ventilation, as used in this report, refers to the intentional and accidental supply of outdoor air to a building. Ventilation is necessary to control indoor air concentrations of indoor-generated air pollutants. From an energy efficiency perspective, the amount of ventilation during hot and cold weather should be minimized because ventilation air must often be heated or cooled and dehumidified.

Prior research has shown that occupants in offices and schools with higher ventilation rates are more satisfied with air quality, have fewer sick-building-syndrome symptoms such as irritation of eyes and nose, and have a slightly higher level of work performance (Fisk et al. 2009; Seppanen et al. 2006; Seppanen et al. 1999; Sundell et al. 2011). Two prior studies have also found lower absence rates in buildings with higher ventilation rates (Milton et al. 2000; Shendell et al. 2004).

The energy use associated with ventilation in commercial buildings has been estimated via simulations of the existing building stock (Benne et al. 2009). An estimated nine percent of energy used in the stock of U.S. commercial buildings is attributable to heating and cooling ventilation air supplied mechanically with fans and through uncontrolled air infiltration through the building envelope. No comparable estimates are available for California's commercial buildings, but in California the fraction of total building energy attributable to ventilation is likely to be comparable or moderately smaller.

Given the impacts of ventilation on both indoor environmental quality and energy consumption, in the selection of ventilation rates, one must strike a balance between these two important concerns. Minimum ventilation standards have been established that specify minimum design ventilation rates for various types of buildings. In California, these minimum ventilation rates are specified in the California Building Energy Efficiency Standards (California Energy Commission 2008) or Title 24 Standards. For most building types, the minimum ventilation standards specify minimum ventilation rates that are the larger of a minimum rate per person and a minimum rate per unit floor area. However, due to a paucity of data the scientific underpinning for current minimum ventilation standards is relatively weak, particularly for buildings other than offices.

One key element of this research project, discussed in Chapter 6, was designed to help fill the gap in knowledge related to minimum ventilation requirements in classrooms. In a large multiyear field study, this research investigated how classroom ventilation rates affected student absence rates.

A larger portion of the current research project, discussed in Chapter 2 through Chapter 5, focused on a technology for controlling ventilation rates called demand-controlled ventilation. The demand-controlled ventilation systems investigated are ones that automatically modulate ventilation rates as occupancy changes. The goal is to avoid excessive ventilation and associated unnecessary energy use when spaces are unoccupied or have a lower than normal occupancy.

Demand-controlled ventilation systems are most commonly used in spaces with a high and variable occupant density, such as meeting rooms and are required for such spaces in California (California Energy Commission 2008). Demand-controlled ventilation is sometimes also used in spaces with a lower but variable occupancy such as general office areas.

Much of the research on demand-controlled ventilation in the current project focused on an performance evaluations of sensors used to indirectly or directly sense the occupancy level in a space or building. Other components of the research investigated where sensors should be located within meeting rooms and the potential energy savings from using demand-controlled ventilation in general office spaces within California. This research led to a number of specific recommended changes to specifications for demand-controlled ventilation in Title 24.

CHAPTER 2: Accuracy of CO_2 Sensors Used for Demand-Controlled Ventilation

2.1 Background

People produce and exhale carbon dioxide (CO_2) as a consequence of their normal metabolic processes; thus, the CO_2 concentrations inside occupied buildings are higher than the CO_2 concentrations in the outdoor air. The magnitude of the indoor-outdoor concentration difference decreases as the building's ventilation rate per person increases. If the building has a nearly constant occupancy for several hours and the ventilation rate is nearly constant, the ventilation rate per person can be estimated from the maximum steady state difference between indoor and outdoor CO_2 concentrations (ASTM 1998; Persily 1997). For example, under steady conditions, if the indoor CO_2 concentration in an office work environment is 700 parts per million above the outdoor concentration, the ventilation rate is approximately 7.5 L/s (15 cfm) per person (ASHRAE 2007). In many buildings, occupancy and ventilation rates are not stable for sufficient periods to allow indoor CO_2 concentrations to equilibrate sufficiently for accurate determinations of ventilation rates from CO_2 data; however, CO_2 concentrations remain an approximate, easily measured, and widely used proxy for ventilation rate per occupant. The difference between the indoor and outdoor CO_2 concentration is also a proxy for the indoor concentrations of other occupant-generated bioeffluents, such as body odors (Persily 1997).

Epidemiological research has found that indoor CO_2 concentrations are useful in predicting human health and performance. Many studies have found that occupants of office buildings with a higher difference between indoor and outdoor CO_2 concentration have, on average, increased sick building syndrome health symptoms (Seppanen et al. 1999). In a study within a jail, higher CO_2 concentrations were associated with increased respiratory disease (Hoge et al. 1994). Higher CO_2 concentrations have been associated with increased student absence in schools (Shendell et al. 2004) and office worker absence (Milton et al. 2000). Additionally, a recent study (Shaughnessy et al. 2006) found poorer student performance on standardized academic performance tests correlated with increased CO_2 in classrooms and Wargocki and Wyon (2007) found that students performed various school-work tasks less rapidly when the classroom CO_2 concentration was higher.

In a control strategy called demand-controlled ventilation (Emmerich and Persily 2001; Fisk and de Almeida 1998), CO_2 sensors, sometimes called CO_2 transmitters, are deployed in commercial buildings to obtain CO_2 data that are used to automatically modulate outdoor air supply rates. The goal is to not only keep ventilation rates at or above design requirements, but also to adjust the outside air supply rate with changes in occupancy to save energy by avoiding over-ventilation relative to design requirements. Demand-controlled ventilation is most often used in spaces such as meeting rooms with variable and sometimes dense occupancy. Some buildings use CO_2 sensors just to provide feedback about ventilation rates to the building operator, without automatic modulation of ventilation rates based on the measured CO_2 concentrations.

In nearly all cases, each of the CO_2 sensors deployed for demand-controlled ventilation measure CO_2 concentrations at a single indoor location. In this report, these sensors are referred to as single-location CO_2 sensors. A small number of buildings utilize CO_2 sensors connected to tubing, valves, and pumps for CO_2 concentration measurements at multiple indoor locations as well as outdoors. In this report, these systems are referred to as multilocation CO_2 measurement systems.

Research literature on demand-controlled ventilation (Apte 2006; Emmerich and Persily 2001; Fisk and de Almeida 1998) indicated a significant potential for energy savings, particularly in buildings or spaces with a high and variable occupancy. Based on energy modeling (Brandemuehl and Braun 1999), cooling energy savings from demand-controlled ventilation applications are as high as 20 percent. However, there have been many anecdotal reports of poor CO_2 sensor performance in actual demand-controlled ventilation applications. Also, pilot studies of sensor accuracy in California buildings indicated substantial error in the measures made by many of the evaluated CO_2 sensors (Fisk et al. 2007).

Based on the prior discussion, there is a good justification for monitoring indoor CO_2 concentrations and using these concentrations to modulate outdoor air supply rates. This strategy will only be effective if CO_2 sensors have a reasonable accuracy in practice.

This chapter provides the results of research performed to evaluate the in-situ accuracy of CO_2 measurement systems used for CO_2 demand-controlled ventilation and, to the degree possible via analyses of the data, to determine how accuracy varies with sensor age and sensor technical features. The primary focus was the accuracy of the most commonly used type of CO_2 sensor that measures CO_2 at a single indoor location. A small preliminary evaluation of CO_2 measurements made with multilocation sampling systems was also performed to provide an initial indication of the potential of CO_2 monitoring using more expensive, and thus potentially more stable and accurate, CO_2 sensors coupled with multilocation sampling systems. Systems that employ multilocation sampling equipment to measure CO_2 concentrations at multiple locations using the same CO_2 sensor are much less common than distributed single-location sensors. Multilocation systems have advantages and disadvantages. Multilocation system advantages include the use of one sensor to measure at multiple locations potentially reducing total sensor costs, the potential to spend more to obtain a higher quality sensor if it is used for multiple-location measurements, the ease of calibrating a single or small number of sensors relative to calibrating many sensors, and the potential to include an outdoor CO_2 measurement in each building, or preferably, with each CO_2 sensor. Also in some cases, the multilocation sampling system may be usable to measure contaminants other than CO_2. Disadvantages include the need for a multilocation sampling system of tubing, valves, and pumps, the potential for leakage-related errors with multilocation sampling system, the need for a sample pump, and the reduced frequency in which CO_2 concentration data are available from each location. In an additional task, spatial variability of CO_2 concentrations in meeting rooms was evaluated to provide information to aid selection of sensor locations.

One additional research component was an evaluation of a small sample of single-location CO_2 sensors that had large errors, with the goal of identifying causes of sensor inaccuracy.

2.2 Methods

2.2.1 Field Studies of Single-Location CO_2 Sensor Performance

The research on single-location CO_2 sensors, hereinafter called sensors, was performed in two phases. The pilot study phase supported by the U.S. Department of Energy evaluated the performance of 43 CO_2 sensors located in nine buildings in California. The second study phase supported by the California Energy Commission evaluated the performance of 165 sensors from 25 buildings in California. This report presents and analyzes the data from both study phases, with a total of 208 sensors located in 34 buildings. Two different protocols were employed to assess the accuracy of the CO_2 sensors. When possible, bags of primary standard CO_2 calibration gases were used to evaluate sensor performance at five CO_2 concentrations from 230 to 1780 parts per million (ppm). This procedure is referred to as a multiconcentration calibration check. Based on the calibration gas supplier specifications and the protocols employed, the calibration gas concentrations were known within about 5 percent. In the multiconcentration calibration checks, the CO_2 sensors located in buildings sampled each of the calibration gas mixtures. The CO_2 concentrations reported on the building's data acquisition system display or on the CO_2 sensor display, or when possible at both locations, were recorded. The data obtained was processed to obtain a zero offset error and slope or sensor gain error using a least-squares linear regression of measured CO_2 concentration versus true reference CO_2 concentration. If a sensor agreed exactly with the true concentration, then the zero offset error would be zero and the sensor slope would equal the true concentration slope (unity). However, a 50 ppm offset error would indicate that the sensor would read 50 ppm high at a concentration of 0 ppm, and 50 ppm high at all CO_2 concentrations if the sensor's slope is unity. A slope of 0.8 would indicate that reported concentration slope plotted versus true concentration is 0.8. The multiconcentration calibration process also yielded errors at each of the calibration gas concentrations. The three calibration gas concentrations used that are most representative of the CO_2 concentrations typically encountered in buildings are 510, 760, and 1,010 ppm. The multiconcentration calibrations were performed when the CO_2 sensors had an inlet port and the sensor had a concentration display or the building operator was able and willing to program the data acquisition system so that data was provided with sufficient frequency (for example, every several minutes) to make a multipoint calibration possible with calibration gas bags of a practical volume. This type of performance test was completed for 90 sensors from 19 buildings.

When a multiconcentration calibration check was not possible, single-concentration calibration checks of the building's CO_2 sensors were performed using a colocated and calibrated reference CO_2 instrument. The protocol was very simple. A calibrated research-grade CO_2 instrument was taken to the building where its calibration was checked with primary standard calibration gas samples. The reference instrument was placed so that it sampled at the same location as the building's CO_2 sensor. Data from the reference instrument was logged over time. CO_2 concentrations reported on the sensor's display or the building's data acquisition system's screen, or at both locations, were recorded manually. The data was processed to obtain an absolute error, equal to the CO_2 concentration reported by the building's data acquisition system minus the true CO_2 concentration. This sensor performance check type was completed for 118 sensors located in 24 buildings, including single-concentration calibration checks of sensors for which multiconcentration calibrations were also completed. One limitation of the single-concentration calibration data is that much of the data was obtained with CO_2 concentrations below 500 ppm, with an average concentration of 466 ppm. For subsequent analyses, the data from the single-concentration calibration checks was combined with the data obtained using the 510 ppm calibration gas in the multiconcentration calibration checks of sensors. The resulting data set is called the combined dataset, which contained data from 207 sensors in 34 buildings[3].

The reference CO_2 instrument used for the single-point calibrations has an automatic zero feature and is calibrated with a span gas. The rated accuracy is better than 1 percent of span concentration but is limited by the calibration gas mixture accuracy. In this study, the span gas concentration was 2,536 ppm and rated at ± 2 percent accuracy. Multiconcentration calibration checks of this reference instrument were also performed using precision span gas dilutions during field site visits. Figure 1 shows an example of the deviations between the reference instrument output and the concentration of CO_2 in the diluted span gas. The deviations range from approximately +1 percent to – 2 percent. To further evaluate the accuracy of measurements with the reference instrument, it was used to measure the CO_2 concentration in nine additional calibration gas mixtures, all distinct from the span gas routinely used for instrument calibration checks. As shown in Figure 2, the reference instrument output deviated from the reported calibration gas concentration by approximately -1 percent to -5 percent. Given these data, the uncertainty in CO_2 concentration measurements made with the reference instrument is estimated to be 5 percent or less.

[2] One of the multipoint sensor calibrations lacked data at 510 ppm for combination with the single point data.

Figure 1: Example of Measurement Errors of Reference CO_2 Instrument When Measuring Precise Dilutions of the Span Gas

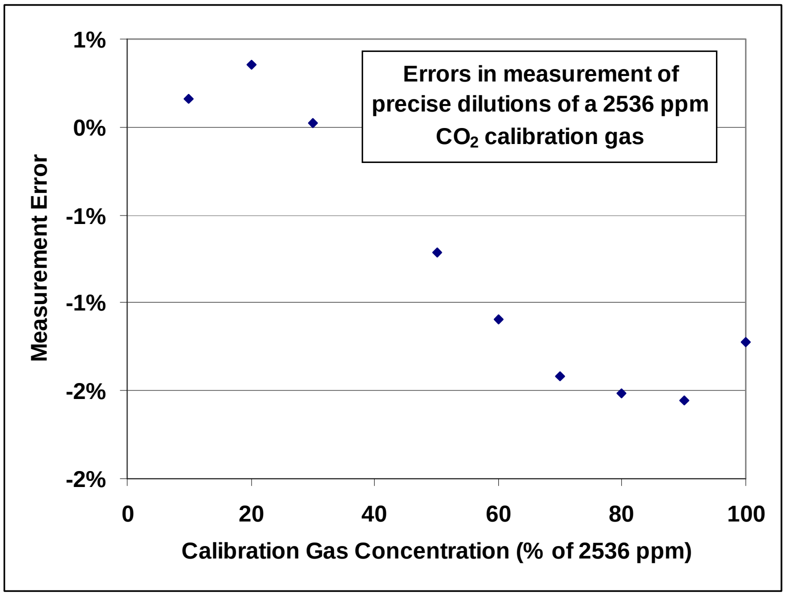
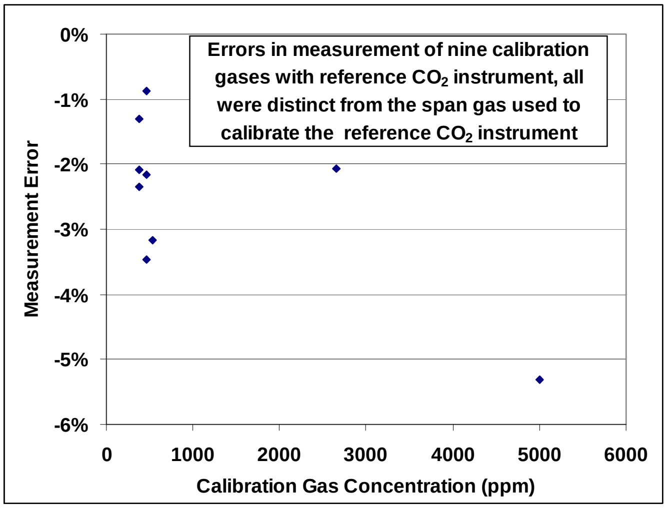


Figure 2: Errors in Measuring the Concentration of Nine CO_2 Calibration Gases with the Reference CO_2 Instrument



All of the CO_2 sensors evaluated were nondispersive infrared sensors. The sensors generally have a default measurement range of zero to 2,000 ppm. Nearly all sensors sampled via diffusion, for example, had no sample pump. The manufacturers' accuracy specifications translate into maximum errors of ± 40 ppm to ± 100 ppm at a concentration of 1,000 ppm if the sensor range is zero to 2,000 ppm. The manufacturers' recommended calibration frequency ranged from every six to 12 months for older products to never needing a calibration under normal conditions, with a five year recommended calibration interval being common. Some sensors use two lamps or two wavelengths of infrared energy in a process to correct for potential drift sources in sensor calibration, for example, to correct for diminished lamp infrared energy output (National Buildings Controls Information Program 2009). For analysis purposes, sensors were classified into the following four design categories: single lamp, single wavelength; dual lamp, single wavelength; single lamp, dual wavelength; or unknown when product literature did not specify the design. In this classification scheme, lamp refers to the infrared source(s) and wavelength refers to the wavelength(s) of infrared energy detected by the sensor's detector. Based on product literature, some sensors perform a self-calibration or auto-calibration. In many instances, this self-calibration automatically resets the sensor calibration based on a complex algorithm and the lowest sensor responses encountered during a prior period. This automatic calibration process assumes that the lowest encountered CO_2 concentration is approximately 400 ppm; for example, that the CO_2 concentration at the sensor location drops to the outdoor air CO_2 concentration. However, product literature for some sensors simply refers to a self-calibration without providing details, and for many sensors the product literature does not indicate whether or not there is a self-calibration feature.

For analyses of how various sensor features related with sensor accuracy, sensors were assigned a manufacturer code number (1 to 10 plus 11 for a few sensors locked in a box with an unknown manufacturer), a sensor design code, a self-calibration code, and a sensor age. Sensors were assigned the sensor design code based on a review of product literature. The sensor design code numbers and corresponding sensor designs were as follows:

1 = known single lamp single wavelength;

2 = suspected single lamp single wavelength;

3 = dual lamp single wavelength;

4 = single lamp dual wavelength;

5 = unknown.

For many sensors, the sensor design code could not be determined due to the lack of product design literature. Sensors were also grouped into the following two categories: sensors in which product literature refers to a self-calibration feature (normally automatic baseline control) and other sensors. This categorization is crude. The dual lamp and dual wavelength sensor designs are intended to automatically correct for sources of error which could be considered a form of self-calibration, but normally the product literature for these sensors did not refer to a self-calibration.

Facility managers were asked about the sensor age; for example, the time elapsed since sensor installation in the building, the CO_2 concentration set point used to trigger an increase in ventilation rate, the sensor calibration history, and the sensor cost. In general they provided only estimates of sensor ages, some did not know the set point, and almost none provided any specific information on costs. No facility manager reported that they had calibrated the sensors since their initial installation in the building. For analysis purposes, an age of six months was assigned for sensors characterized by the facility manager as new. When a facility manager indicated that a sensor was more than n years old, n was assigned as the sensor age.

Bivariate statistical analyses were performed using the anova and regress commands in STATA version 10. For the multiconcentration calibration checks, outcomes were the absolute value of error at 760 and 1,010 ppm. For the combined single-concentration and multiconcentration calibration data, the outcome was absolute error at the concentration encountered or at 510 ppm concentration. Outcome variables were log-transformed to produce normally-distributed residuals with a constant variance, as is required for valid inference from ANOVA and linear regression models. Groups with fewer than 11 observed concentrations were excluded from the analysis. Pairwise comparisons of groups were performed using the Tukey wholly significant difference method with α=0.05. This method makes it more difficult to reject the null hypothesis in each individual pairwise comparison. Additionally, sensor types were analyzed using both the individual types (1 through 5) and groupings of type 1 and 2 versus types 3, 4, and 5. Sensor age was treated as a categorical variable with groups 0-1 year, 1.5-3 years, 3.5-5 years, and 5-7 years for the combined dataset and groups 0-1 year, 1.5-3 years, and 3.5-7 years for the multiconcentration dataset. Linear regression was performed on the log-transformed year, using the robust standard errors option.

Multivariate statistical analyses were performed using the regress command with the robust standard error option specified for both the combined dataset and the multiconcentration dataset on its own. All outcomes (absolute error, absolute error at 760 ppm, absolute error at 1,010 ppm) were log-transformed to meet the assumptions for regression. A dummy variable was created for each sensor grouping category with categories containing very few observations combined into another category. Sensor age was introduced as a categorical measure with categories defined as in the bivariate analysis.

The sensor performance checks, for single-location sensors, were all performed in commercial buildings located in California, selected without consideration of building age or type of CO_2 sensor. The buildings were used for healthcare, education, software industry, judicial, library, utility, corrections, law enforcement, museum, entertainment, retail, and state and federal and private office applications. There were 10 CO_2 sensor brands[4] and multiple model types of some brands.

[3] Some of the manufacturers market sensors from other manufacturers.

2.2.2 Evaluation of Faulty Single-Location CO_2 Sensors

Nine of the single-location CO_2 sensors that had large measurement errors (range 255 to 858 ppm, average 458 ppm) based on the assessments described in Section 2.2.1, were obtained for further evaluation in the laboratory. To obtain the sensors, facility managers were offered a new replacement sensor if they would provide a specified existing sensor for evaluation. In the prior field studies, these sensors had received only a single-concentration calibration check using a colocated and calibrated reference CO_2 instrument. Sensors from four different manufacturers and with different design features were obtained. The following evaluation protocol was implemented.

The first step in the evaluation was designed to evaluate the sensor responses at multiple CO_2 concentrations after 11 days of sensor operation in a highly ventilated room with outdoor air CO_2 concentrations. After this conditioning period, during which automated background calibration software may have corrected some of the sensor calibrations, CO_2 concentrations in the room were normally equal to the outdoor air concentration. Periodically, pure CO_2 was added to room air in amounts sufficient to increase concentrations to approximately 500, 700, 1,000, and 1,500 ppm and the air in the room was mixed using fans. A reference CO_2 instrument continuously monitored CO_2 concentrations within the room. The output signal of the sensors was logged continuously. The resulting data were analyzed to determine measurement errors and whether they were stable.

The second step was to implement the manufacturer's recommended sensor calibration protocols when possible and then to reassess sensor performance using the protocols described in the previous paragraph. For two sensors, the manufacturer provided no calibration protocol. Four sensors had no response or only a very small response to changing CO_2 concentrations. One sensor had an output signal problem that caused the data acquisition system to fail. Thus, a manufacturer's recommended calibration could only be implemented for two sensors. For one of these sensors, the manufacturer's protocol utilized only a calibration gas with no CO_2. For the other sensor, the manufacturer's protocol utilized both a 0 ppm CO_2 calibration gas and a 2,000 ppm CO_2 calibration gas.

The third evaluation step was to remove the sensor covers and have an electronics expert visually inspect each sensor for any electronics component failures. Based on a discussion with the research director of a sensor company and an examination of the limited technical information available from sensor manufacturers, it was determined that detailed electronic sensor performance studies were not feasible. Output measurement of the IR lamps was also not feasible as neither lamp output data nor evaluation protocols were available and most sensor lamps were inside optical cells that could not be opened without destroying the unit.

In the final step in the evaluations, the optical cells of each sensor were opened and the cells visually inspected under low power magnification for signs of cell surface soiling or corrosion.

2.2.3 Pilot Evaluation of CO_2 Demand-Controlled Ventilation with Multilocation Sampling Systems

The accuracy of multilocation CO_2 measurement systems was evaluated in two buildings. The same manufacturer provided the multilocation systems used in both buildings. There are two additional manufacturers of multilocation CO_2 measurement systems, but one manufacturer has only a few installations and was not able to provide convenient access for the studies and the second manufacturer was identified after data collection took place.

The two multilocation CO_2 measurement systems that were evaluated employ tubing, valves, and a pump to draw air from multiple indoor locations to the same sensor. In one building, three measurement systems, each with its own CO_2 sensor, are employed to measure at 45 locations. In the second building, one system is used to measure CO_2 at 27 locations. The tubing is a carbon nanotube and fluoropolomer blend designed to transport particles and some other contaminants (for example, volatile organic compounds) without losses to the tubing walls. No performance evaluations were performed for the tubing relative to these design goals. Special tubing is not critical for transporting CO_2, as CO_2 is a highly volatile and relatively unreactive gas much less subject to depositional losses on tubing walls than particles and many volatile organic compounds. In each building, the outdoor-air CO_2 concentrations as well as the indoor CO_2 concentration at multiple locations are measured. The ventilation control algorithms are based on the difference between indoor and outdoor CO_2 concentrations. Consequently, sensor offset errors can cancel out, for example, if a system measured both the indoor and outdoor CO_2 concentration as 100 ppm greater than the true concentration, there would be no error in the difference between indoor and outdoor concentration. This manufacturer offers a sensor exchange service in which approximately every six months, the manufacturer sends the user recently-calibrated CO_2 sensors and the user returns their previously-used sensors to the manufacturer for calibration.

The evaluation protocols were very similar to the protocols described above for single-location sensors. In one building, the systems were challenged with multiple bags of calibration gases that have known CO_2 concentrations. The bags were attached to sample inlet points for three-to-four measurement cycles. In this building, and in the second building, colocated calibrated reference CO_2 instruments were also employed to evaluate measurement accuracy.

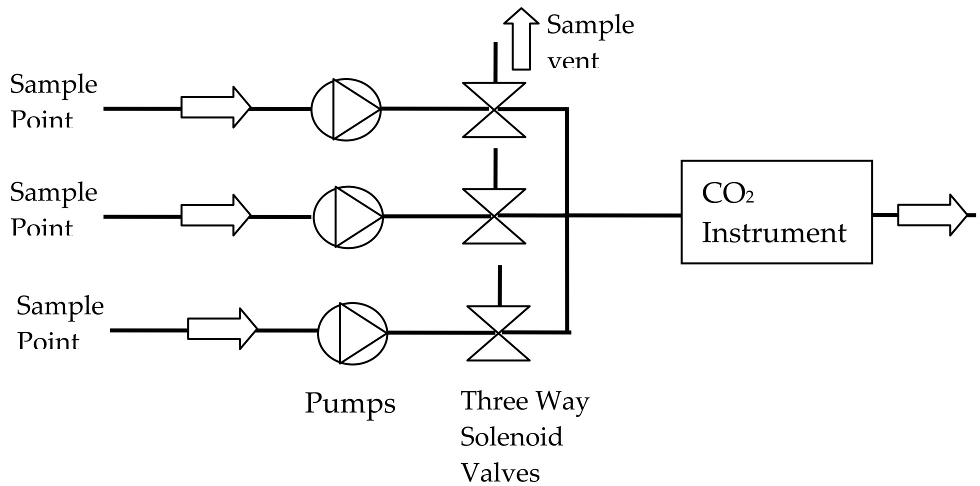
When multiconcentration calibrations were performed, large volumes of calibration gas mixtures were necessary because of the large sample flow rates of the building's CO_2 measurement systems – initially 20 L/minute after switching to a new sample location. It was impractical to transport (via commercial aircraft) multiple bags with sufficiently large volumes of the calibration gas mixtures to the study site. Consequently, bags of calibration gas mixtures were prepared on site by mixing indoor air and a small amount of pure CO_2 in a gas sample bag. The concentrations of CO_2 in the resulting sample bags were determined on-site with the calibrated reference CO_2 analyzer before and after the bags were used to check the response of the building's CO_2 measurement systems. The multiconcentration calibration protocol was developed in consultation with the manufacturer of the multilocation CO_2 measurement system to assure purging of sample lines and instrumentation with the calibration gas samples.

The facility managers for the buildings with the multilocation CO_2 measurement systems were asked the installation date, the reason for selecting the system, the initial system cost (no initial cost data were supplied directly by facility managers), the CO_2 set point, the calibration practices and costs, how the CO_2 data were utilized, and about their experience with the system. Because facility managers did not provide cost data, installed costs estimates were obtained from the manufacturer.

2.2.4 Pilot Evaluation of Spatial Variability of CO_2 Concentrations in Meeting Rooms

The field studies included multipoint CO_2 concentration measurements in six meeting spaces suitable for demand-controlled ventilation. CO_2 concentrations were measured once per minute at various locations and heights on meeting room walls and in return air grilles. Figure 3 shows one of three measurement system schematics, each with the capability for measurements at three locations. Samples were drawn continuously from each sample point. Sequential activation of the three-way solenoid valves for a 20 second periods directed air from specific sample points to the CO_2 instrument, which is the same type of instrument described above as the reference CO_2 instrument. When a solenoid valve was not activated, the sample stream was vented. The continuous sampling through the sample inlet tubes maintained the tubes purged so that data could be collected at high frequency. The system was calibrated using bags of primary standard calibration gas mixtures attached at the inlet end of the sample lines. The CO_2 instrument output was logged continuously and reported every two seconds. Approximately 10 to 12 seconds after solenoid valve activation, the output signal from the CO_2 instrument was stable if the concentration at the sample tube inlet line was stable, indicating purging of the sample hardware downstream of the three-way valve and equilibration of the instrument response. The output signal from the subsequent sample period was converted to the CO_2 concentration using the calibration data for the CO_2 instrument. The system was tested before use and the CO_2 instrument was calibrated at each installation location.

Figure 3: Schematic Representation of One of Three Systems Employed to Rapidly Measure Indoor Carbon Dioxide Concentrations at Three Indoor Locations per System



The three systems provided measurements at nine locations. In general, the measurement locations included a location on each wall at approximately a 1.5 m (5.0 ft.) above the floor (a typical height at which sensors were installed in field settings), inside one or two return grilles, at lower and higher heights (typically 0.4 and 1.7 m or 1.5 and 5.5 ft.) at one of the walls, and a supply air register. In some spaces, the measurement heights had to be adjusted to accommodate wall mounted equipment, such as white boards or display screens. Based on the data, one of the supply airstreams may have contained only recirculated room air. In one meeting room, many chairs were placed immediately adjacent to parts of some walls and sample locations were selected away from these chairs to reduce the impacts of exhaled air with very high CO_2 concentrations.

2.3 Results

2.3.1 Field Studies of Single-Location CO_2 Sensor Performance

2.3.1.1 Multiconcentration Calibration Checks of Single-Location Sensors

Table 1 provides the primary results from the multiconcentration calibration checks of 90 sensors. The first row of data provides the evaluation results of all 90 sensors and subsequent rows provide results for overlapping subsets of the sensors. Data from each sensor is provided in Appendix A. For the full set of sensors, the average slope was 0.97 and the average of the absolute value of zero offsets was 79 ppm. The averages of the absolute values of error were 118 ppm (16 percent) and 138 ppm (14 percent), at concentrations of 760 and 1,010 ppm, respectively. The calibration data are generally well fit by a straight line as indicated by the high R^2 values. For subsets of the full sensor sets, the accuracy is often significantly better or worse than for the full set of sensors. For example, sensors from Manufacturer 4 and 5, sensors with the Type 1 design (single lamp and single wavelength) or with Type 2 design (suspected single lamp and single wavelength design), and sensors with a manufacturer-reported self-calibration system tend to have a better-than-average average accuracy. However, the variability in sensor accuracy within each category is large, as indicated by standard deviations that are often comparable to or larger than the average error for the category.

Figure 4 provides frequency distributions for the slope, zero offset, error at 760 ppm, and error at 1,010 ppm that clearly illustrate the high variability in accuracy. In each case, the error parameters are approximately normally distributed. Figure 5 shows how error at the 760 and 1,010 ppm concentration varies with manufacturer code and the figure provides the average absolute value of error for each category. Sensors from Manufacturers 4 and 5 have substantially lower average absolute value errors at 1,010 ppm, and sensors from Manufacturer 2 also have the lowest average absolute value error at 760 ppm. Figure 6 shows that the lowest average absolute value errors are associated with sensor design type 1 (single lamp single wavelength) and sensor design type 2 (suspected single lamp single wavelength design) at 1,010 ppm. There is a substantial overlap in the sensors within these categories associated with better accuracy; for example, the sensors from Manufacturers 4 and 5 generally had a single lamp single wavelength design and their literature refers to a self-calibration procedure.

As illustrated by the frequency distribution plots in Figure 4, a significant fraction of sensors had errors substantially larger than 100 ppm. For example, at 1,010 ppm, 19 percent of sensors had an error greater than 200 ppm and 13 percent of sensors had errors greater than 300 ppm.

Error is plotted versus sensor age in Figure 7. Given the large standard deviations, indicated by the error bars, there is no clear trend in error with sensor age in the multiconcentration calibration data.

Table 2 provides the proportion of sensors in various categories that had errors greater than ±75 ppm and greater than ±100 ppm at calibration gas concentrations of 760 ppm and 1,010 ppm. For the full set of sensors subject to the multiconcentration calibration checks at 1,010 ppm, 40 percent and 31 percent of sensors had errors greater than ±75 ppm and ±100 ppm, respectively. At 760 ppm, 47 percent of sensors had errors greater than ±75 ppm and 37 percent of sensors had errors greater than ±100 ppm. These proportions varied substantially with manufacturer, sensor design type, and with versus without a self-calibration procedure. Sensors with type 1 (single lamp single wavelength) and type 2 (suspected single lamp single wavelength) designs and those with a self-calibration performed best at 1010 ppm with 12 percent to 14 percent having an error greater than ±100 ppm and just over 20 percent having an error exceeding ±75 ppm. However, at 760 ppm, 36 percent to 48 percent of these same sensors had errors exceeding the same criteria.

Table 1: Primary Results of the Multiconcentration Calibration Checks of 90 Sensors

Sensor Group ___	No. Sensors ___	Slope		Linearity R^2		Zero Offset		Error at 760 ppm		Error at 1010 ppm		ABV (Zero Offset)		ABV (Error at 760 ppm)		ABV (Error at 1010 ppm)	
		Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
		----	----	----	----	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
all sensors	90	0.97	0.28	0.97	0.10	14	113	-26	200	-9	258	79	83	118	163	138	218
Manu. 1	4	0.71	0.48	0.79	0.42	-9	36	-235	360	-324	478	27	21	247	349	342	461
Manu. 2	2	0.35	0.08	0.72	0.06	-95	26	-737	27	-774	38	95	26	737	27	774	38
Manu. 4	29	0.91	0.12	0.99	0.02	66	98	1	72	-21	98	88	78	49	52	69	72
Manu. 5	33	0.97	0.09	0.99	0.02	12	84	-37	131	-4	124	59	60	100	91	70	102
Manu. 6	5	1.01	0.21	1.00	0.00	43	26	51	174	61	239	43	26	93	151	134	198
Manu. 7	16	1.19	0.49	0.98	0.03	-67	166	64	252	153	385	124	127	179	184	281	299
Type 1	26	0.95	0.06	1.00	0.00	30	76	16	71	10	80	64	49	49	53	53	59
Type 2	17	0.98	0.06	0.98	0.01	-28	45	-126	35	-45	53	45	26	126	35	49	49
Type 3	2	0.41	0.59	0.57	0.59	-25	43	-476	396	-650	507	30	35	476	396	650	507
Type 4	27	1.06	0.42	0.98	0.03	1	168	34	198	68	318	116	120	125	156	204	250
Type 5	18	0.90	0.25	0.97	0.09	57	95	-32	296	-48	325	80	75	156	250	190	265
No Self-Cal.	39	0.99	0.42	0.95	0.15	8	152	-17	288	1	386	101	112	176	226	250	291
Self-Cal.	51	0.95	0.07	0.99	0.01	19	73	-34	88	-17	72	62	43	73	58	53	52
Age 0 – 1 yr	26	1.09	0.43	0.98	0.03	7	166	81	181	121	307	109	123	119	157	204	258
Age 1.5 - 3 yr	23	0.98	0.06	0.98	0.02	-15	47	-91	69	-32	55	42	25	99	55	46	44
Age 3.5 - 7 yr	37	0.94	0.10	1.00	0.00	45	94	2	132	-11	149	82	65	75	108	88	120

Key: ABV = absolute value, Avg = average, Cal. = calibration, Manu = manufacturer, SD = standard deviation, Type 1 is single lamp single wavelength, Type 2 is suspected single lamp single wavelength, Type 3 is dual lamp single wavelength; Type 4 is single lamp dual wavelength; Type 5 = unknown type

Figure 4: Frequency Distributions of Key Results From the Multiconcentration Calibration Checks

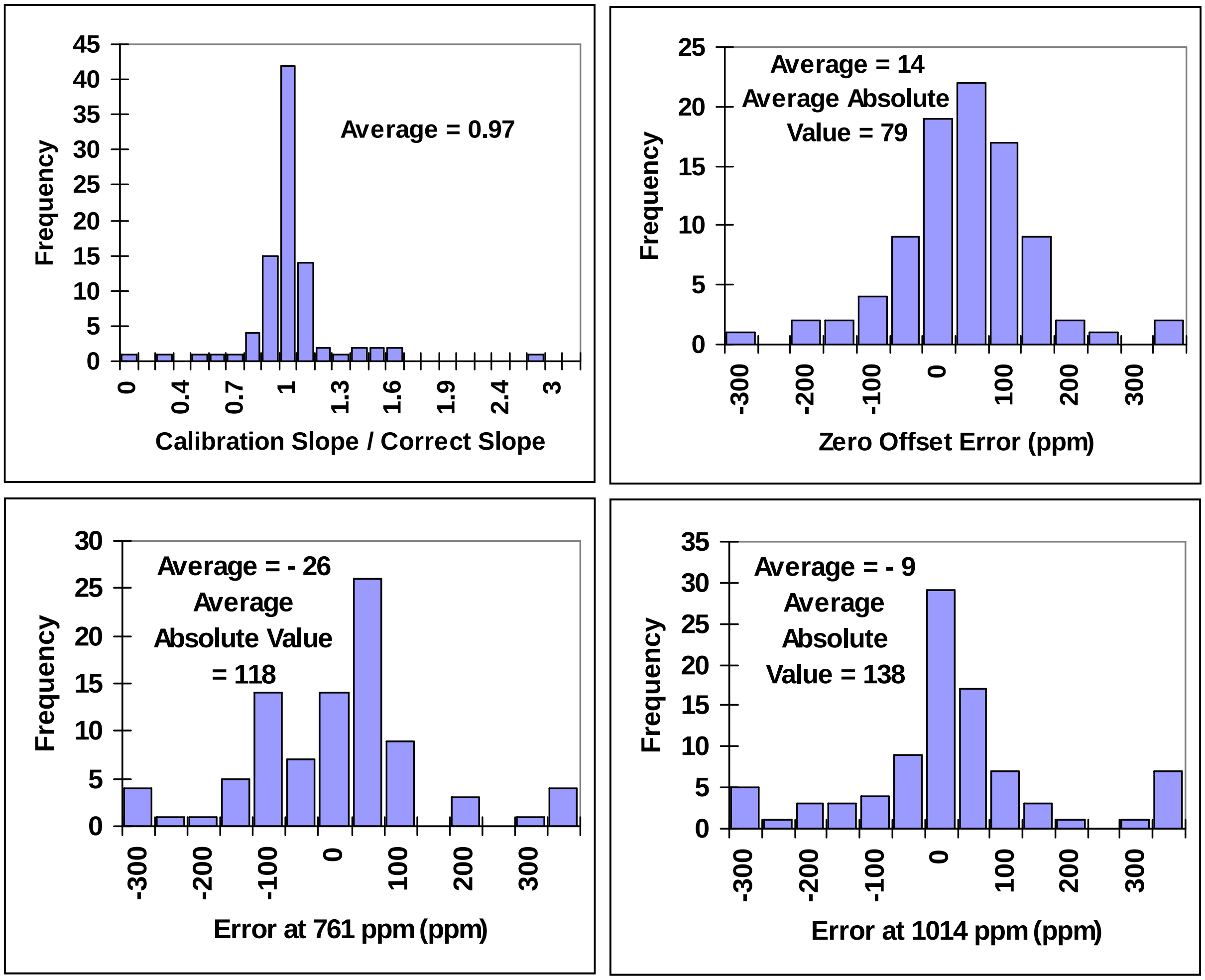


Figure 5: Errors at 760 and 1010 ppm Versus Manufacturer Code from Multiconcentration Calibration Checks

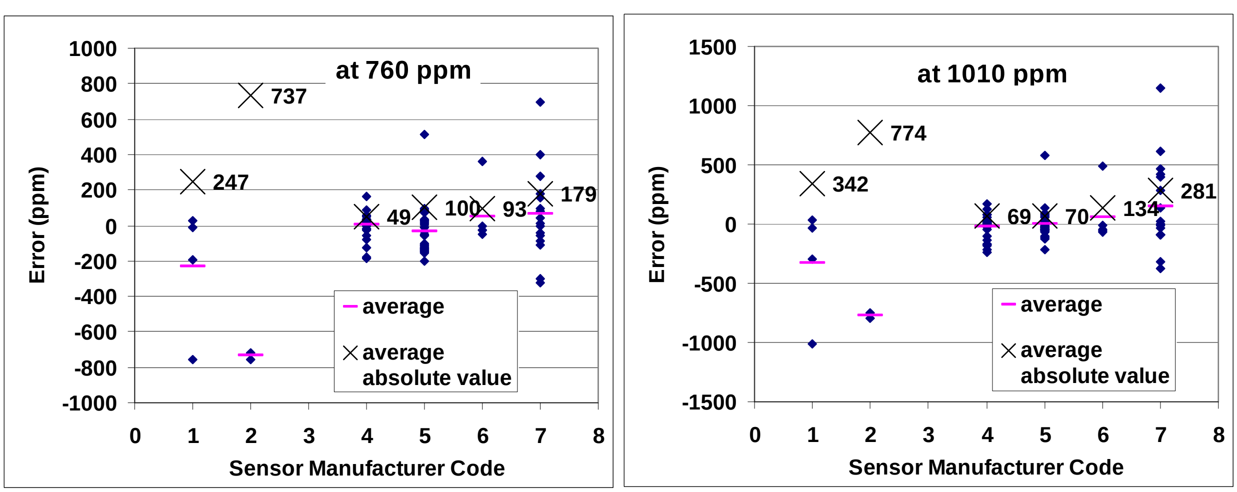


Figure 6: Errors at 760 and 1010 ppm Versus Sensor Design Type from Multiconcentration Calibration Checks

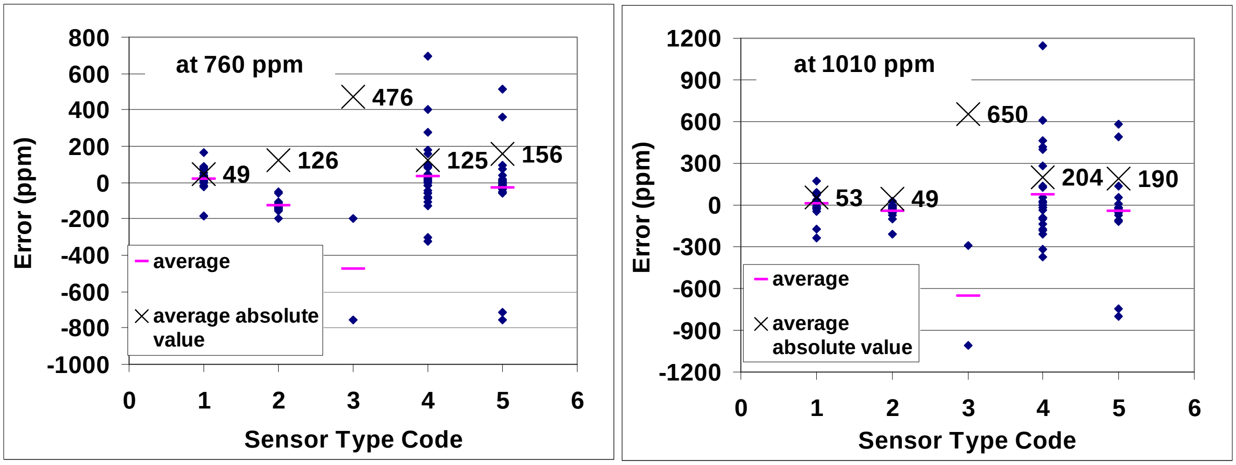


Figure 7: Errors at 760 and 1010 ppm Versus Sensor Age from Multiconcentration Calibration Checks. Error Bars Represent One Standard Deviation in the Error

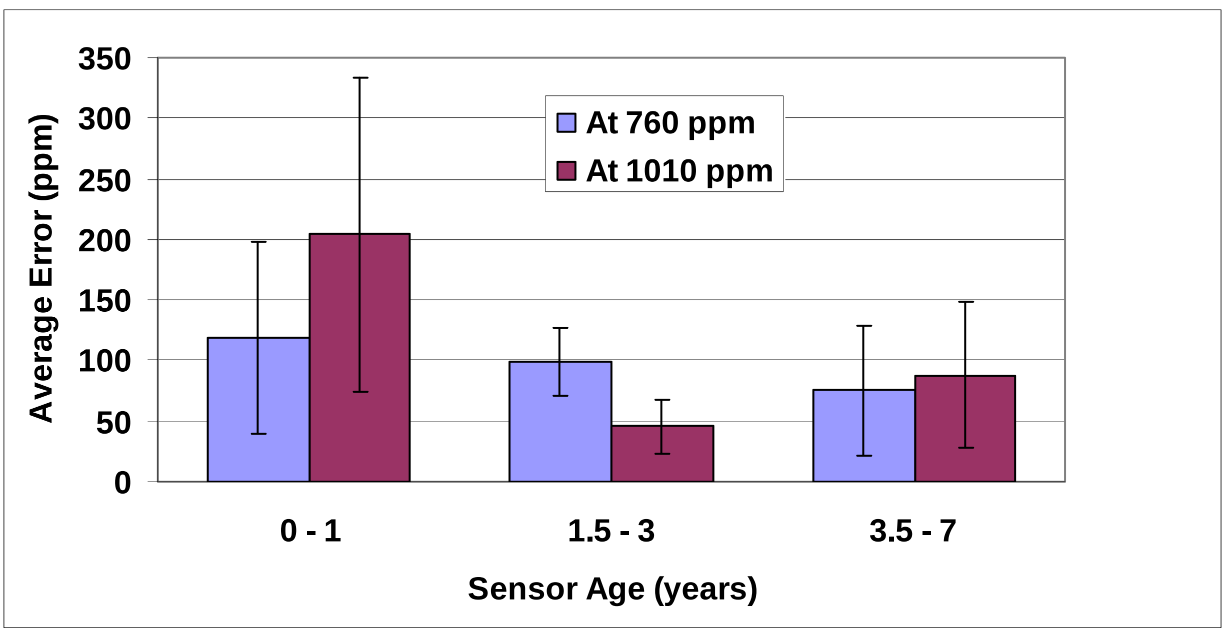


Table 2: Proportions of CO_2 Sensors in Various Sensor Categories With Errors Greater Than ±75 and ±100 Ppm in the Multiconcentration Calibration Checks

Sensor Group	No. of. Sensors	--------At 760 ppm-------		--------At 1010 ppm-----	
		Proportion with error > ±75 ppm	Proportion with error > ±100ppm	Proportion with error > ±75 ppm	Proportion with error > ± 100ppm
all sensors	90	0.47	0.37	0.40	0.31
Manu. 1	4	0.50	0.50	0.50	0.50
Manu. 2	2	1.00	1.00	1.00	1.00
Manu. 4	29	0.21	0.14	0.37	0.27
Manu. 5	33	0.61	0.48	0.24	0.18
Manu. 6	5	0.20	0.20	0.20	0.20
Manu. 7	16	0.69	0.50	0.75	0.56
Type 1	26	0.20	0.12	0.27	0.12
Type 2	17	0.88	0.88	0.12	0.12
Type 3	2	1.00	1.00	1.00	1.00
Type 4	27	0.52	0.33	0.67	0.52
Type 5	18	1.00	0.22	1.00	0.39
Type 1 - 2	43	0.48	0.43	0.21	0.12
Type 3 - 5	47	0.47	0.32	0.57	0.49
No Self-Cal.	39	0.54	0.38	0.64	0.54
Self-Cal.	51	0.42	0.36	0.22	0.14

Manu = manufacturer; Cal = calibration, Type 1 is single lamp single wavelength, Type 2 is suspected single lamp single wavelength, Type 3 is dual lamp single wavelength; Type 4 is single lamp dual wavelength; Type 5 = unknown type

2.3.1.2 Combined Data Set

Table 3 provides the primary data results from the single-concentration calibration checks combined with the data from challenging sensors with a 510 ppm calibration gas in the multiconcentration calibration checks. Data for individual sensors are provided in Appendix A. For the full set of 207 sensors, the average error was 60 ppm and the average of the absolute value of error was 154 ppm. The standard deviations associated with these two averages were high, 263 ppm and 222 ppm, respectively. Considering only categories with greater than 10 sensors, average absolute value of error was smallest for Manufacturer 5 (58 ppm) and for sensor design types 1 and 2 (66 ppm and 24 ppm, respectively). Again, sensors with a self-calibration designated in product literature had a lower average absolute value error (83 ppm versus 218 ppm). The error absolute value average increased with sensor age. However, the standard deviations in the errors in each category were generally larger than the average errors.

Table 3: Primary Results of the Single-Concentration Calibration Checks and Multiconcentration Calibration Challenges at 510 ppm

Sensor Group	No of. Sensors	---------- Error --------		-------- Average Absolute Value of Error -------			
		Average (ppm)	Standard Deviation (ppm)	Average (ppm)	Standard Deviation (ppm)	Proportion > 75 ppm	Proportion > 100 ppm
All sensors	207	60	263	154	222	0.43	0.36
Manu 1	13	-110	250	206	172	0.77	0.77
Manu 2	2	-504	2	504	2	1.00	1.00
Manu 3	19	278	359	364	190	0.84	0.74
Manu 4	57	35	261	125	231	0.35	0.28
Manu 5	49	38	100	58	90	0.16	0.12
Manu 6	5	37	117	62	104	0.20	0.20
Manu 7	22	-60	329	177	281	0.50	0.41
Manu 8	14	269	278	271	276	0.79	0.57
Manu 9	6	66	48	66	48	0.33	0.33
Manu 10	3	18	67	45	45	0.33	0.00
Manu 11	17	151	177	159	170	0.41	0.35
Type 1	48	32	96	66	76	0.27	0.17
Type 2	22	16	28	24	22	0.05	0.00
Type 3	11	-131	268	243	161	0.91	0.91
Type 4	34	-23	269	131	235	0.41	0.32
Type 5	92	138	322	228	265	0.55	0.49
Types 1 and 2	70	27	81	53	67	0.20	0.11
Types 3 - 5	137	76	317	205	253	0.55	0.48
No Self-Calibration	109	56	335	218	260	0.57	0.51
With Self-Calibration	98	64	150	83	140	0.28	0.18
Age 0 – 1 yr	46	51	114	80	95	0.35	0.26
Age 1.5 - 3 yr	47	87	201	109	190	0.34	0.21
Age 3.5 - 5 yr	66	79	284	165	244	0.37	0.31
Age 5 – 7 yr	35	46	371	244	287	0.66	0.63

Manu = manufacturer; Type 1 is single lamp single wavelength, Type 2 is suspected single lamp single wavelength, Type 3 is dual lamp single wavelength; Type 4 is single lamp dual wavelength; Type 5 = unknown type

Figure 8 shows the roughly normal error frequency distribution and Figure 9 shows errors plotted versus sensor manufacturer and sensor design type. These figures illustrate the large error variability within each sensor category.

Average and standard deviation of error were plotted versus sensor age in Figure 10. There is a trend toward higher absolute value of error with increased sensor age; however, the standard deviations in error for each age category are large.

The proportions of all 207 sensors with absolute values of error exceeding 75 ppm and 100 ppm were 43 percent and 36 percent, respectively (Table 3). These proportions varied substantially among the overlapping subcategories of sensors. These high errors were found in smaller proportions of sensors from Manufacturers 5 and 6, with design types 1 and 2, and with a manufacturer-specified self calibration procedure.

Figure 8: Frequency Distribution of Error from Single-Concentration Calibration Checks and Multiconcentration Calibration Challenges at 510 ppm

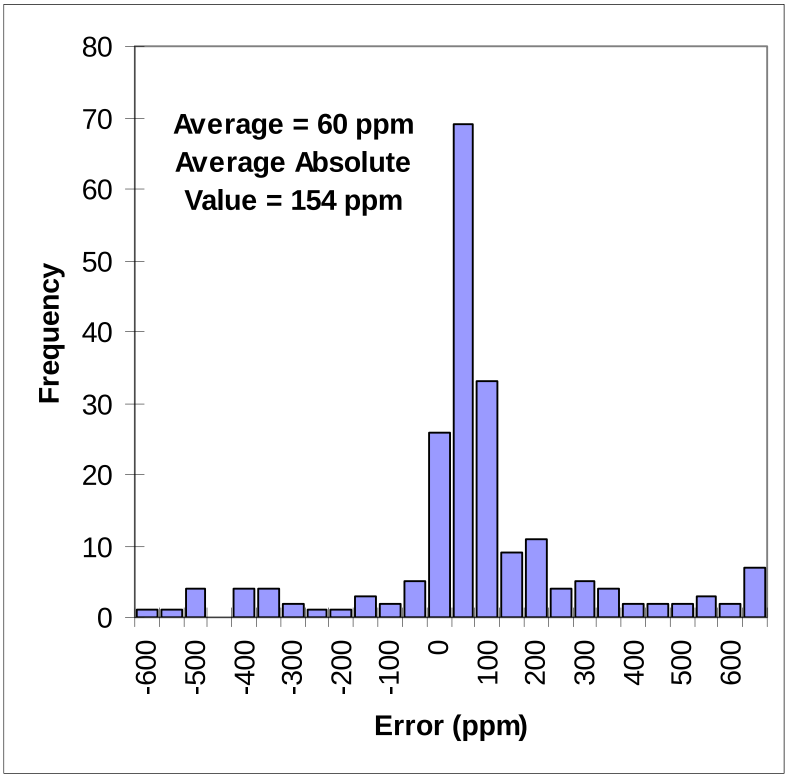


Figure 9: Error from Single-Concentration Calibration Checks and Multiconcentration Calibration Challenges at 510 ppm Plotted Versus Manufacturer and Sensor Design Type

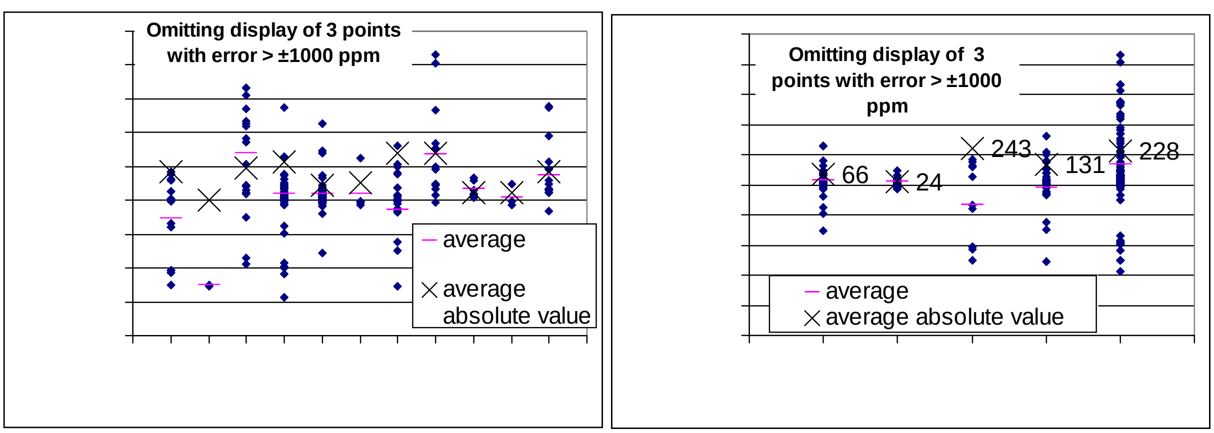
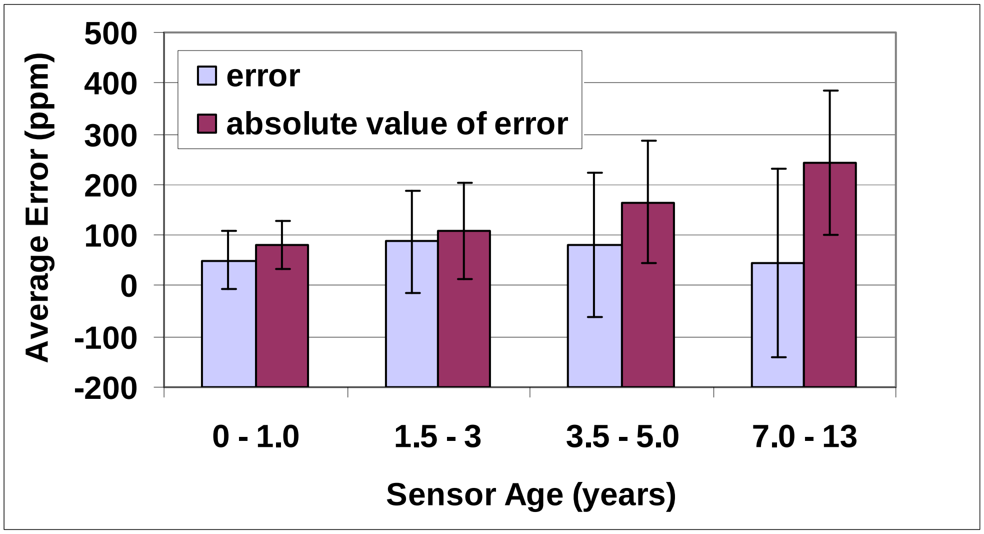


Figure 10: Error from Single-Concentration Calibration Checks and Multiconcentration Calibration Challenges at 510 ppm Plotted Versus Sensor Age Error Bars Represent One Standard Deviation in the Error



2.3.1.3 Carbon Dioxide Concentration Set Points

In only 13 of the 25 buildings within the Energy Commission-supported studies the facility manager provided data on the indoor CO_2 set point concentration above which the demand-controlled ventilation system increased the ventilation rate. Asking facility managers for set point concentrations was not part of the protocol in the initial pilot study supported by the U.S. Department of Energy. Within eleven of these buildings, the same set point concentration was reported for all sensors. The reported set point concentrations ranged from 500 ppm (one instance) to 1,100 ppm. The building-weighted average set point concentration was 860 ppm, if one uses the sensor-weighted averages for buildings with multiple set point concentrations for the building-weighted calculation. The most frequently reported set point concentration was 800 ppm, which was reported for all sensors in four buildings and also reported for some sensors in two additional buildings.

2.3.1.4 Repeatability of Errors

Multiconcentration calibration checks were repeated for four sensors. In every case, the resulting slope of the repeat measurement differed by 0.01 or less from the original slope. The zero offsets differed by 16 ppm or less, with an average deviation of 8 ppm. The error at the 1,010 ppm challenge concentration repeated within 16 ppm or less with an average deviation of 9 ppm.

Single-concentration calibration checks were repeated for five sensors. For three sensors the resulting error repeated within 18 ppm or less. For one sensor the error in the repeat test was 113 ppm larger than the error in the initial test. For the fifth sensor, the single-concentration check was repeated twice when the investigators noticed a large discrepancy and suspected a possible procedural error. The first repetition yielded an error 60 ppm different than the first test while the error in the second repetition was only 9 ppm different from that in the first repetition.

2.3.1.5 Errors from Energy Management Systems Versus Sensor Displays

Because the main objective of this research was to evaluate sensor accuracy, primary analyses relied on data from sensor displays whenever available. However, for 38 sensors in six buildings, all where multiconcentration calibration checks were performed, data were collected from both the sensor display and the energy management system's computer display. The errors at the 510 ppm, 760 ppm, and 1,010 ppm challenges of the 38 sensors yielded 113 instances in which errors based on data from the energy management systems could be compared to errors based on sensor display measurements. The average of the absolute value of the difference between the paired estimates of error was 25 ppm; however, excluding data from two sensors located within the same building, the average difference was 10 ppm. For the two sensors in which data from the energy management system and sensor display differed dramatically, the average absolute value difference was 290 ppm. For at least one of these sensors, it was clear that the energy management system's data was not from the correct sensor. In general, these findings indicate that the substantial measurement errors found in this study are sensor errors, not errors in translating the sensor output signals to the energy management systems.

2.3.1.6 Statistical Significance of Differences in Sensor Accuracy

Table 4 lists the results of the sensor error statistical analyses. The table lists paired categories of sensors for which the average absolute value errors were statistically significantly different, for example, 95 percent confidence intervals excluded unity. In bivariate analyses, sensors from Manufacturer 4 (and to a more limited extent from Manufacturer 5) tended to have significantly smaller errors than errors from most of the other manufacturers. Also, sensor type 1 (single lamp single wavelength) tended to have smaller errors than other sensor types except type 4 (single lamp dual wavelength). In some cases, sensors with a reported self-calibration had statistically significantly smaller errors than sensors without a reported self-calibration. In general, error was not significantly associated with sensor age. Many of the differences found to be statistically significant in bivariate analyses remained significant in the multivariate analyses, except self-calibration was no longer a significant predictor of error. Presumably self-calibration is correlated with sensor manufacturer and sensor type, which are better error predictors. The multivariate analyses identified a few statistically significant differences in average errors that were not evident in the bivariate analyses, possibly because the bivariate analysis method is slightly more conservative.

Table 4: Differences in Averages of Absolute Value Errors That Were Statistically Significant (p<0.05)*

		Analyses	
Dataset	**Category**	**Bivariate**	**Multivariate**
Multi-Concen-tration Calibration Challenge, 760 ppm	Manufacturer Sensor Type Self-Calibration Sensor Age	Error (M4) < Error (M5, M7) Error(T1) < Error(T2) --- ---	Error(M4) < Error(M7) Error(T1) < Error(T2) Error (T5) < Error(T2) --- ---
Multi-Concen-tration Calibration Challenge, 1010 ppm	Manufacturer Sensor Type Self-Calibration Sensor Age	Error(M4) < Error(M7) Error(M5) < Error(M7) Error(T1+T2) < Error(T3+T4+T5) Error(with SC) < Error(without SC) ---	--- --- --- ---
Combined	Manufacturer Sensor Type Self-Calibration Sensor Age	Error(M4) < Error(M3, M8) Error(M5) < Error(M3, M7, M8) Error(M7) < Error(M3) Error(T1) < Error(T3, T5) Error(T2) < Error(T3, T5) Error(T4) < Error(T3) Error(T1+T2) < Error(T3+T4+T5) Error(with SC) < Error(without SC) Error(Age 0–1 yrs) < Error(Age 5–7 yrs)	Error(M1) < Error(M4) Error(M4) < Error(M3, M7, M8) Error(M5) < Error(M3, M8) Error(T1) < Error(T3) Error(T2) < Error(T3) Error(T4) < Error(T3) Error(T5) < Error(T3) --- Error(Age 3.5–5 yrs) < Error(Age 5–7 yrs)

*Subcategories are indicated by the following symbols: M1 – M8 = manufacturer 1 – manufacturer 8; T1 – T5 = sensor type 1 – sensor type 5, where T1 is single lamp single wavelength, T2 is suspected single lamp single wavelength, T3 is dual lamp single wavelength; T4 is single lamp dual wavelength; T5 = unknown. SC = self calibration

2.3.2 Evaluation of Faulty Single-Location CO_2 Sensors

Table 5 provides descriptive information for the faulty single-location CO_2 sensors evaluated in the laboratory and the major evaluation findings. These faulty sensors are from four manufacturers, have multiple design types, and are two to 13 years old. Four of the nine sensors had either no output signal or had an output signal that changed little or none as the CO_2 concentration varied. A fifth sensor repeatedly caused the data acquisition system to shut down, thus, it could not be subjected to tests. Measurements showed that the sensor's output voltage was highly erratic and the sensor repeatedly attempted to reinitialize its operation. Thus, five of nine sensors were essentially nonfunctional, although four of these were approximately 13 years old. Sensor FS4 had stable errors which varied with CO_2 concentration between 240 ppm to 410 ppm before the manufacturer's zero and span gas calibration protocol were implemented; subsequently, its errors were 33 ppm to 76 ppm (Figure 11). Sensor FS5, which had a 310 ppm error in the field setting, had errors of 0 ppm to 95 ppm in the laboratory (after the conditioning period) and these errors did not change significantly after implementing the manufacturer's calibration protocol which involved only use of a zero-CO_2 gas. Sensors FS6 and FS7 had fluctuating errors of five to 158 ppm and 79 ppm to 310 ppm, respectively, during the laboratory studies. The errors were much smaller than the approximately 800 ppm errors in the field setting for both of these sensors, which came from the same building. The smaller errors observed in the laboratory studies of Sensors FS5 – FS7, relative to the errors observed for the same sensors in the field studies, might be a consequence of automatic calibration corrections during the 11 days of sensor deployment in the laboratory (if CO_2 concentrations in the field setting were not regularly decreasing to the outdoor CO_2 concentration) and for FS7 the trends suggest further improvements in accuracy, Figure 12. Another possibility is that there were signal processing problems in the field settings. These sensors had no output displays; therefore, the original field studies of the accuracy of these sensors accuracy relied on the CO_2 concentrations reported by energy management systems.

An electronics expert visually inspected the sensor electronics and indicated no visually obvious electronics failures except in the one sensor with an erratic output voltage that caused the data acquisition system to shut down. In this sensor, an electrical pin that extended out the back of the circuit board and plugged into a socket in the wall mounting plate had a loose pin. This electrical pin became totally disconnected from the circuit board during the inspection process.

The visual inspections of optical cells indicated small particle deposits or corrosion on the reflective surfaces of the optical cells on six sensors. The deposit or corrosion amounts were never large enough to be a definite source of sensor malfunction. One older nonfunctional sensor had a window between the optical cell and detector that was partially soiled or discolored. In two sensors, there were one or more small holes, roughly 0.5 mm in diameter, in the fabric covered openings to optical cells. These fabric covered openings provide the path for CO_2 to diffuse into the cells while excluding airborne particles.

In summary, these evaluations of faulty sensors did not identify definite causes of sensor failures. The study did determine that four of the nine sensors had an output signal that was essentially invariable with CO_2 concentration and that a fifth sensor had a highly erratic output signal; for example, the sensors were nonfunctional, yet still deployed. The evaluations did identify slight soiling or corrosion of optical cells and, in two sensors, holes in the fabrics through which CO_2 diffuses into optical cells which may have contributed to performance degradations. In one of two cases when a manufacturer's calibration protocol could be implemented, sensor accuracy was clearly improved after the protocol was implemented.

Table 5: Properties of Faulty Sensors Evaluated in the Laboratory and Key Findings

I.D.	Man No.*	Sen-sor Type#	Self Calibra-tion	Sen-sor Age (yr)	Man has Cal+ Protocol	Summary of Findings	Results of Inspection of Optical Cell
FS1	1	3	--	~ 13	Yes*	very small response to changing CO_2 concentrations	slight soiling of window between cell and detector
FS2	1	3	--	~ 13	Yes*	small response to changing CO_2 concentrations	no evidence of soiling or corrosion
FS3	4	5^	--	~ 13	Yes	no response to changing CO_2 concentrations	hole in fabric covered opening to cell; scattered particle deposits
FS4	4	1	yes	5	Yes	large accuracy improvement after implementing manufacturer's recommended calibration protocol	no evidence of soiling or corrosion
FS5	5	1	yes	2	Yes	fair to good accuracy after 11 days; errors fluctuated up to 60 ppm; accuracy not improved after implementing manufacturer's calibration	soiling or corrosion of cell near lamp
FS6	8	5#	yes	3	No	error initially ~ 500 ppm at ~ 1200 ppm, avg. error ~ 50 ppm at 1000 ppm after 11 days, errors fluctuated up to 150 ppm	scattered minor pits or soiling of cell walls
FS7	8	5+	yes	3	No	error initially ~ 500 ppm at ~ 1200 ppm, avg. error ~ 60 ppm at 1000 ppm after 11 days, errors fluctuated up to 230 ppm	scattered minor pits or soiling of cell walls
FS8	4	1	yes	~13	Yes	no output signal	multiple holes in fabric covered openings to cell
FS9	4	1	yes	3	Yes	highly erratic output signal caused data acquisition system to shut down,	loose electrical pin (see text), no evidence of soiling or corrosion

*Man = Manufacturer #Type 1 is single lamp single wavelength, Type 3 is dual lamp single wavelength; Type 5 = unknown type +Cal = Calibration ^single lamp # dual lamp **hardware required for calibration is no longer available

Figure 11: Improvement in Accuracy of Sensor FS4 after Implementing the Manufacturer's Recommended Calibration Protocol

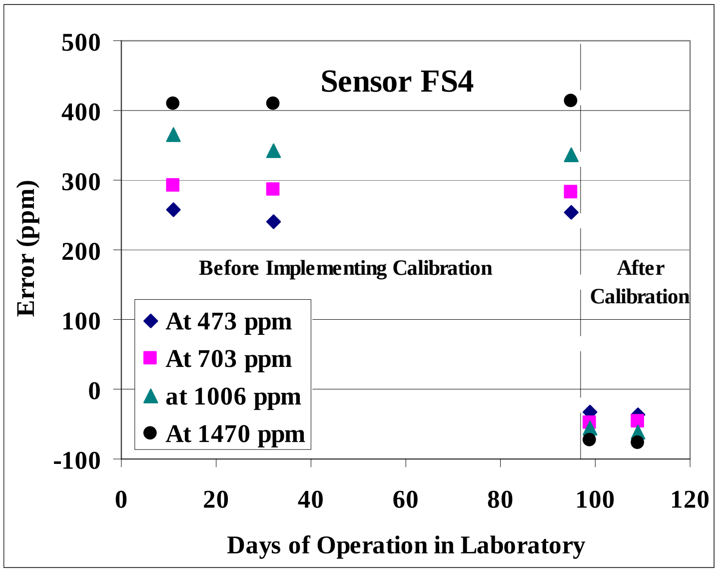
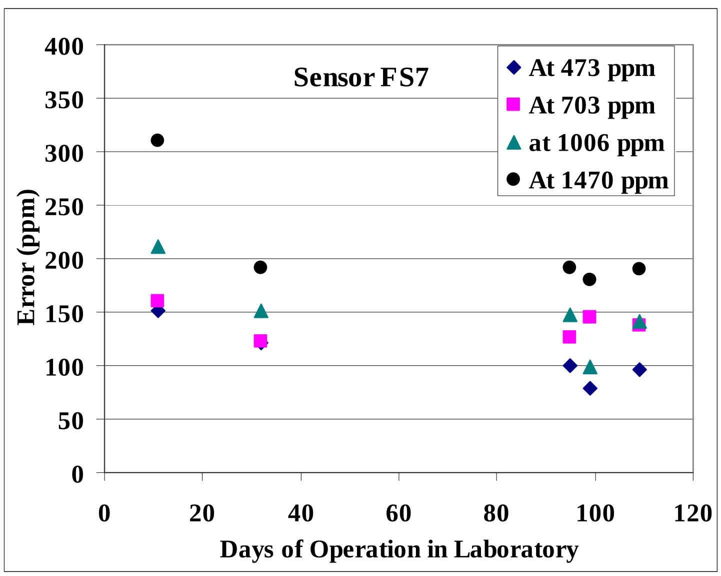


Figure 12: Improvement in Accuracy of Sensor FS7 during Early Period of Operation in the Laboratory



2.3.3 Pilot Evaluation of CO_2 Demand-controlled Ventilation with Multilocation Sampling Systems

In Building M1, the challenges with calibration gas mixtures were implemented twice to evaluate three multilocation CO_2 measurement systems. Data from the first protocol implementation were judged potentially unreliable because the bags of calibration gases may not have been installed on the sample inlet tubes for a sufficient period; thus, these data have not been utilized. The initial data were reviewed with the manufacturer who, prompted by the test results, evaluated the system and identified and fixed some leaks in the sampling system, prior to the second implementation of the multiconcentration calibration protocol. The data obtained from studies in Building M1 may not be typical of data for this CO_2 monitoring system. In addition to employing the multiconcentration calibration protocol, the accuracy of CO_2 measurements in Building M1 was also measured using the calibrated reference CO_2 instrument which measured CO_2 concentrations for approximately 30 minute periods at the same locations of the building's multilocation CO_2 measurement systems. Table 6 provides the results from these studies. The average and standard deviation of error in indoor CO_2 concentration when the systems were challenged with calibration gas mixtures with CO_2 concentrations of 525 to 953 ppm was 69 ppm and 40 ppm, respectively. In 13 of 18 cases, the error was less than 25 ppm. For the same concentration range, the average and standard deviation of error in indoor minus outdoor CO_2 concentration difference were 14 ppm and 39 ppm, respectively, and in 16 of 18 cases the error was 36 ppm or smaller. Errors were markedly higher at reference CO_2 concentrations of 1,680 and 1,844 ppm, but errors in measurements at such high concentrations, which should not occur in buildings with demand-controlled ventilation, are not particularly important. The interested indoor-outdoor CO_2 concentration difference, which is the appropriate input to the demand-controlled ventilation system, was measured with little error at least at a large majority of the investigated locations.

Figure 13 shows the results of evaluations of the single multilocation CO_2 measurement system in Building M2. The figure compares the concentrations reported by the building's measurement system to the concentrations measured simultaneously with three colocated calibrated reference CO_2 instruments. At all three locations, the building's measurement system utilized the same CO_2 sensor and the measured concentrations were approximately 110 ppm greater than the reference measurements of CO_2 concentration. Outdoor CO_2 concentrations measured by the building's measurement system averaged approximately 510 ppm, which is approximately 110 ppm larger than the typical outdoor air CO_2 concentration. Because the offset error is approximately the same for the indoor and outdoor CO_2 measurements, the error in the difference between indoor and outdoor CO_2 concentration within this building is small. Consequently, as in Building M1 the indoor-outdoor CO_2 concentration difference, which is the appropriate input to the demand-controlled ventilation system, was measured with little error at least at the investigated locations.

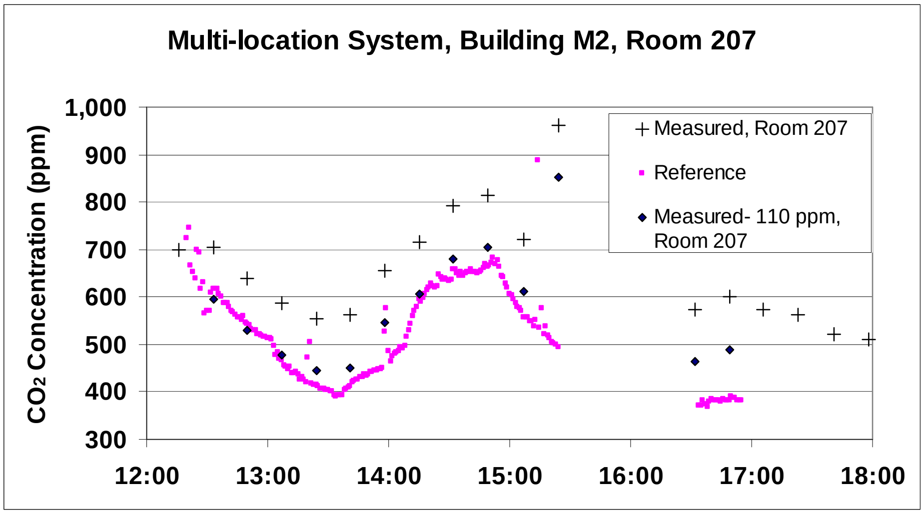
In both buildings, the multilocation CO_2 monitoring system was installed as part of the process to obtain Leadership in Energy and Environmental Design (LEED) certification and utilized for demand-controlled ventilation. Based on a discussion with the facility manager of building M1, the measurement system was one-year old, the CO_2 set point was 800 ppm above the outdoor CO_2 concentration, they experienced no problems with the system, and calibrated sensors were provided every six months via a contract with the manufacturer. From discussions with the facility manager of building M2, the multilocation CO_2 measurement system was 10 months old, the manufacturer provided calibrated replacement sensors four times per year, and there had been some commissioning difficulties but no subsequent system problems. No information on the CO_2 set point was provided.

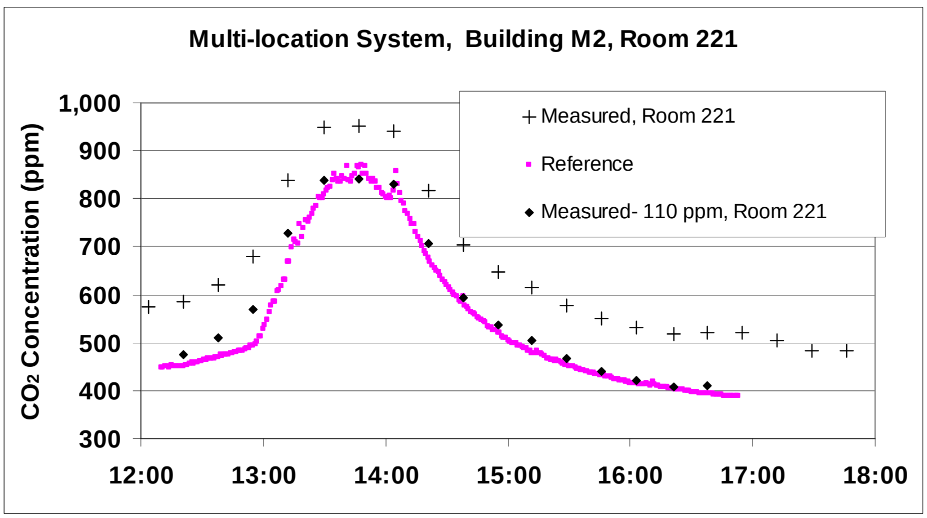
Neither facility manager directly provided information on initial system costs; however, the manufacturer estimated that installed costs were typically $1,500 to $2,500 per sensed location. The system from this manufacturer includes special sampling components that are needed for pollutants other than CO_2, thus, it is not cost optimized for CO_2 – only measurements. The manufacturer's reported cost of calibration services (providing calibrated replacement sensors every six months and replacing sensors when needed), real-time sensor diagnostics, warranty, and data services were estimated to be $60 to $125 per year per sensed location. For comparison, the cost of traditional demand-controlled ventilation with single-location CO_2 sensors used for development of the Title 24 standard is $617 per sensor after adjustment for inflation (Hong and Fisk 2009). However, a $1,540 per sensor cost can be derived from a cost analysis of obtaining LEED certification (Steven Winters Associates 2004).

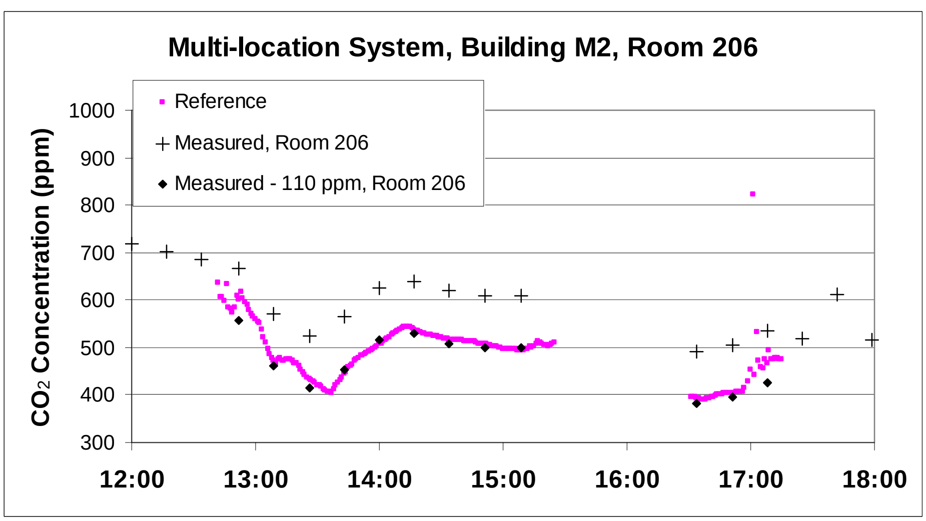
Table 6: Results of Evaluations of Multilocation CO2 Measurement Systems in Building M1

System	Location	Reference CO_2 Concentration (ppm)	Error in Indoor CO_2 Concentration (ppm)	Error in Indoor Minus Outdoor CO_2 Concentration Difference (ppm)
-----------------------Challenges with calibration gasses------------------------				
1	1125	525	80	25
1	3126	525	27	-21
1	3135	525	38	-18
3	1230	569	34	-18
3	2202	569	40	-13
3	2204	569	39	-19
2	4126	570	44	-14
2	5126	570	100	36
2	5163	570	47	-11
3	1230	861	54	-3
3	2202	861	73	22
3	2204	861	64	11
2	4126	867	72	10
2	5126	867	155	98
2	5163	867	78	19
1	1125	953	174	118
1	3126	953	55	0
1	3135	953	73	25
1	1125	1,680	323	276
1	3126	1,680	124	66
1	3135	1,680	131	75
2	4126	1,844	193	133
2	5126	1,844	363	304
2	5163	1,844	200	135
Average and (Standard Deviation) of all results with CO_2 < 1000 ppm			69 (40)	14 (39)
---Evaluation with co-located reference CO_2 instrument-----				
1	2116	427	12	-36
2	5163	543	54	0
2	5163	676	67	11
3	1122	429	31	-24
3	1230	478	36	-23

Figure 13: Results of Evaluations of the Multilocation CO_2 Measurement System in Building M2







2.3.4 Spatial Variability of CO_2 Concentration in Meeting Rooms

Figure 14 provides an example plot of the multipoint, carbon dioxide concentration monitoring results during a noon-time seminar in a crowded 76 m^2 conference room. In this instance, the CO_2 concentrations, varied among locations at any one time by up to approximately 300 ppm, and fluctuated substantially with time at many locations. Concentrations at return grilles were in the middle of the range. The concentration at the west wall location may be lowest because the people were not located close to this location which was directly below the screen used for display of presentations. Concentrations measured at the 0.3 m height on the east wall are moderately lower than concentrations measured at the 1.4 m and 1.8 m heights.

In three of six meeting rooms, concentrations fluctuated rapidly as illustrated in Figure 14, potentially in part because of the CO_2 in exhaled breath from people near sample points. During measurements in meeting rooms 1 and 4, it is known that the rooms were very crowded with people sitting or standing near sample locations. The CO_2 concentrations measured by the sensors used for demand-controlled ventilation applications will most likely vary less, as these sensors sample diffusively and respond more slowly than the instruments used in this research. In the remaining three meeting rooms, concentration fluctuations were less pronounced, as illustrated in Figure 15.

Data similar to those illustrated in Figures 14 and 15 were collected from seven total time periods in six meeting rooms. Table 7 provides information on the meeting rooms and measured CO_2 concentrations. From each data set, period-average (for example, time-average over the selected time period) CO_2 concentrations are provided at each measurement location for periods of 30 minutes to 90 minutes when concentrations were elevated above background due to occupancy of the meeting room. For the example datasets shown in Figure 14 and 15, concentrations were averaged for the 12:15 to 13:00 and 14:10 to 14:55 time periods, respectively. The range in period-average CO_2 concentrations at the wall mounted sample points located in the same meeting room varied from 43 ppm to 242 ppm. In four of seven data sets, the period-average CO_2 concentration at return grilles were within 5 percent of the period average of all CO_2 concentration measurements made at locations on walls, for the other three data sets the deviations were 7 percent, 11 percent, and 16 percent. Return-air CO_2 concentrations were not consistently higher or lower than the average concentration at locations on walls. In four data sets, the period-average return-air CO_2 concentration was between the lowest and highest period-average concentration measured at wall locations, while in the other three data sets the period-average concentrations were lowest at the return grilles. There was no consistent increase or decrease in CO_2 concentrations with height at the three colinear Wall-4 measurement locations, and the concentrations at different walls often varied more than concentrations varied with height at Wall 4. In the four instances with CO_2 measurements at two return-air grilles, the associated two period-average CO_2 concentrations differed by 6 ppm or less.

Figure 14: First Example of Data from Studies of Spatial Distributions of CO_2 Concentrations in Occupied Meeting Rooms

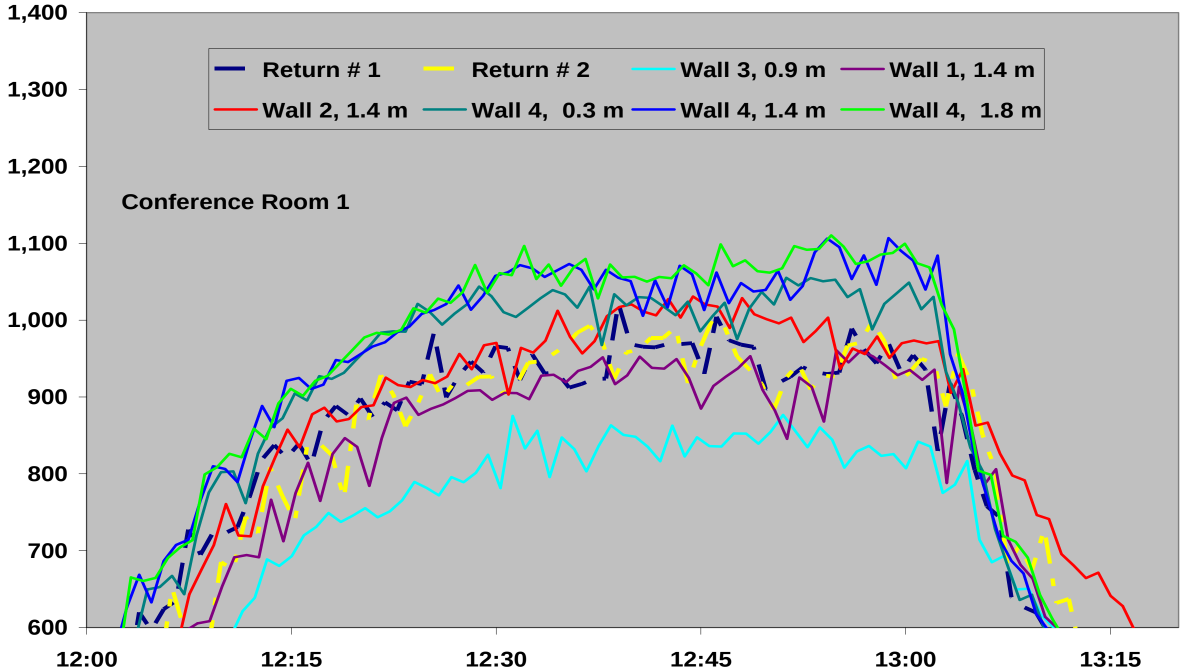


Figure 15: Second Example of Data from Studies of Spatial Distributions of CO_2 Concentrations in Occupied Meeting Room

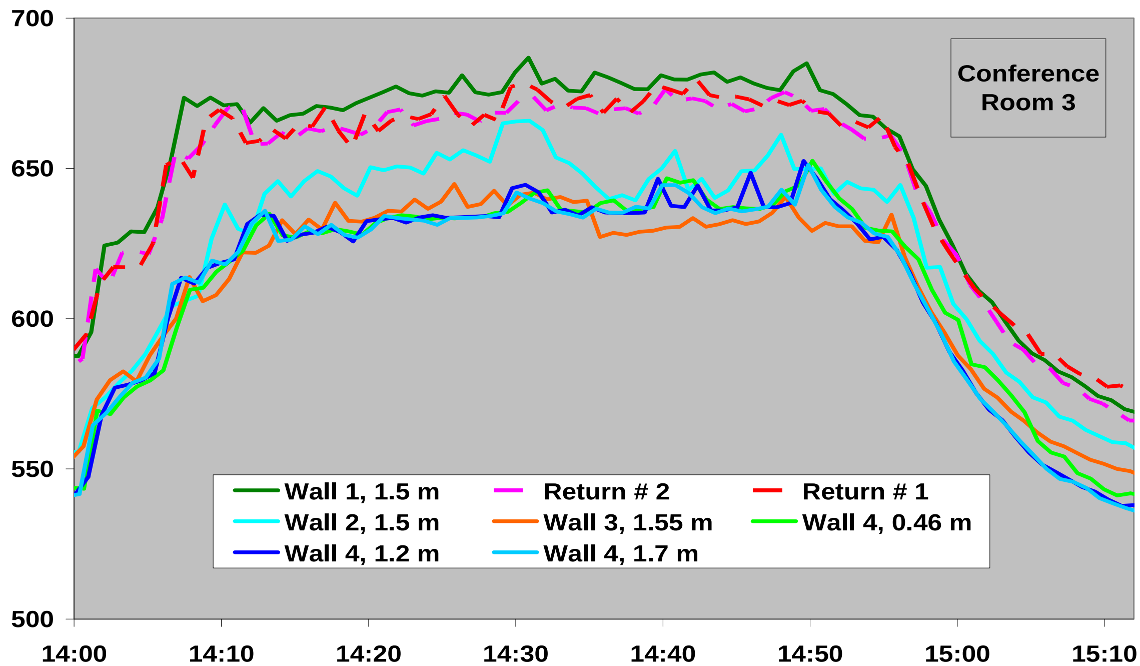


Table 7: Spatial Variability of CO_2 Concentrations in Occupied Meeting Rooms. Numbers Are Averages and Standard Deviations for 30 – 90 Minute Meetings Unless Indicated Otherwise

Conf, Room	1	2	3	3	4	5	6
Floor Area (m^2)	76	45	59	59	160	115	46
Ceiling Height (m)	2.7	2.7	2.8	2.8	2.7 – 4.7	3.0	3.0
CO_2 Concentration (standard deviation) in ppm or Concentration Ratio							
Wall 1	902 (48)	722 (23)	675 (5)	626 (23)	1,668 (185)	943 (145)	640 (68)
Wall 2	960 (51)	724 (32)	648 (8)	599 (16)	1,774 (166)	909 (160)	515 (43)
Wall 3	811 (45)	719 (34)	632 (7)	594 (17)	1,910 (263)	964 (137)	562 (58)
Wall 4 Low	1007 (39)	708 (22)	635 (7)	582 (19)	1,672 (238)	903 (100)	533 (49)
Wall 4 medium	1029 (51)	704 (36)	635 (6)	583 (18)	1,734 (232	961 (153)	554 (61)
Wall 4 high	1042 (53)	651 (64)	634 (6)	584 (18)	1,759 (243)	945 (126)	571 (80)
Wall 5	NA	NA	NA	NA	1,823 (277)	967 (177)	621 (74)
All Wall locations	959 (94)	704 (47)	643 (17)	595 (23)	1,754 (247)	940 (146)	571 (75)
All Wall (max – min)*	231	73	43	43	242	64	124
Return Grille 1	931 (43)	593 (30)	669 (5)	616 (16)	NA	NA	NA
Return Grille 2	925 (54)	596 (34)	668 (5)	615 (17)	1,877 (216)	890 (124)	510 (48)
Return Average / All Wall Average	0.97	0.84	1.04	1.03	1.07	0.95	0.89
Supply	433 (6)	451 (18)	613 (5)	581 (14)	1,413 (150)	849 (130)	424 (5)

*maximum minus minimum of average CO_2 concentrations measured at locations on walls
^return grille was mounted in a wall, not in the ceiling of the meeting room

2.4 Discussion

2.4.1 Accuracy Requirements

To place these study results in context, one must have an estimate of the required CO_2 sensor accuracy used in commercial buildings for demand-controlled ventilation. While most systems only measure the indoor CO_2 concentration, the difference between indoor and outdoor CO_2 concentration is a better indicator of building ventilation rate. As outdoor CO_2 concentrations in urban areas can vary significantly with location and time, one needs to be able to determine with reasonable accuracy the difference between peak indoor and outdoor CO_2 concentrations found in commercial buildings. The most representative data set is that obtained from a survey of 100 office buildings by the U.S. Environmental Protection Agency (EPA). This EPA study measured and recorded five-minute-average CO_2 concentrations at three indoor locations and one outdoor location. If one considers the maximum one-hour average differences between indoor and outdoor CO_2 concentration[5] from this EPA study, the minimum was 55 ppm, maximum was 777 ppm, average was 310 ppm, and median was 269 ppm. If one desires no more than a 20 percent error in measurements of the average peak indoor-outdoor CO_2 concentration difference, then 62 ppm (20 percent of 310 ppm) is a minimum expectation for CO_2 measurement accuracy in offices. The California Title 24 Standard requires a similar level of accuracy the CO_2 sensors must be factory certified to have an accuracy of no less than 75 ppm

[5] Based on the first authors' analyses of the CO_2 data from this study.

over a five year period without recalibration in the field. Seventy five parts per million corresponds to 16 percent of the difference between the average set point concentration (860 ppm) reported in this study and the typical outdoor carbon dioxide concentration of 400 ppm.

2.4.2 Accuracy of Single-Location CO_2 Sensors

This study employed two protocols to evaluate sensor error – multiconcentration calibration checks and single-concentration checks. The data from the multiconcentration calibrations, performed whenever possible, have the greatest value because these data yield estimates of sensor accuracy at typical CO_2 set point concentrations. The errors at 760 and 1,010 ppm may be the most useful indicators of sensor accuracy. The slope and zero offset errors can be counteracting; thus, neither provides a clear indication of overall sensor performance. There is a general consistency among the findings obtained via the two evaluation protocols. The results of both protocols indicate that many sensors had large errors. In general, both protocols indicate that the same subgroups of sensors had superior (or inferior) average performance.

The findings of this research indicate that a substantial fraction of CO_2 sensors had errors greater than specified in Title 24 or provided in the applicable product specifications. Forty seven percent of sensors had errors greater than 75 ppm at a concentration of 760 ppm and 40 percent of sensors had errors greater than 75 ppm at a concentration of 1,010 ppm. A significant fraction of sensors have much larger errors, for example, > 300 ppm. These concentrations of 760 and 1,010 ppm are typical of the set point concentrations at which demand-controlled ventilation systems increase outdoor air ventilation rates. Thus, overall many CO_2 sensors do not meet accuracy requirements

Sensors from specific manufacturers, with a single lamp single wavelength design, and with a self-calibration procedure specified in product literature, had better average accuracy. After multivariate statistical analyses of the data, sensors from some manufacturers had a better average accuracy (particularly Manufacturer 4) and Type 1 sensors (with a single lamp single wavelength design) were generally associated with statistically significantly higher average accuracy. However, use of sensors only in these categories, while helpful, would not result in widespread compliance with the Title 24 accuracy requirements. Twenty one and 37 percent of sensors from Manufacturer 4 and 20 percent and 27 percent of Type 1 sensors still had errors greater than 75 ppm at 760 ppm and 1,010 ppm, respectively.

In general, all or most of the sensors within each building were the same model and had the same or a similar age. Sensor manufacturer and type are correlated with the building identification code. Differences in maintenance and calibration practices among buildings theoretically might partially explain the observed associations of accuracy with sensor manufacturer and features. However, given that none of the facility managers reported that they had calibrated the sensors in their buildings subsequent to the initial sensor installation, the manufacturer and the sensor design are more likely the real explanation for the observed variability in sensor accuracy.

A significant number of sensors in all age sensor categories had large errors. Thus, replacing sensors every few years also would not solve the accuracy problem. The results obtained from the energy management systems generally agreed well with the sensor display results. The measurement errors appear to be primarily a consequence of sensor problems and not a consequence of errors in translating the sensor output signals to building energy management systems. Having a display on the sensor may be advantageous as it facilitates checks of sensor assignment in the energy management software. Also, periodic visual checks of sensor displays could help facility managers identify obviously faulty sensors.

The analyses of a sample of nine faulty sensors failed to identify definite causes of sensor failures. The fact that four of the nine sensors had an output signal that was essentially invariant with CO_2 concentration, yet these sensors were still deployed, indicates that facility managers are not always aware of obviously faulty sensors. These findings suggest that sensor fault detection systems that provide alarms when sensors are clearly faulty (for example, have invariable outputs) may be beneficial for maintaining performance of demand-controlled ventilation systems.

Three of the faulty sensors were 13 years old, the highest sensor age encountered in the study. One might conclude that 13 year old sensors would be expected to be faulty and should have been replaced, although the manufacturer's product literature does not specify a sensor lifetime. However, if we exclude the data from one outlier with an error of 1,486 ppm, the average error of all the 13 year old sensors in the study was the same as the average error of the seven year old sensors. Also, the average error of 7 year old to 13 year old sensors was not statistically significantly higher than the average age of 3.5 to 5 year old sensors. Thus, the study data provide no clear indication of how long sensors should be deployed.

The Iowa Energy Center (National Buildings Controls Information Program 2009) provides the accuracy results from a laboratory-based study of 15 new single-location CO_2 sensor models. Although their report does not provide summary statistics, their findings are broadly consistent with the findings of the field studies of CO_2 sensor accuracy described in this report. Many of the new CO_2 sensors had errors greater than 75 ppm, and errors greater than 200 ppm were not unusual. Maximum errors for new sensors approached 500 ppm.

It is important to keep in mind that the reference CO_2 measurements used in this study to evaluate sensor accuracy are imperfect. The reference CO_2 instrument linearity, cross comparisons with other instruments, and performance checks using multiple calibration gases instill confidence in the reference measurements; however, errors of a few percent are still likely. If these errors were systematic, the reported average errors of CO_2 sensors installed in buildings and reported fractions of sensors with large errors could change significantly; however, the main findings and conclusions of this research are not likely to be substantially impacted by errors in the reference CO_2 measurements.

2.4.3 Accuracy Multilocation CO_2 Monitoring Systems

The data from the pilot studies of the accuracy of multilocation CO_2 monitoring systems are insufficient as a basis for any firm conclusions about the accuracy of these systems; however, the limited results obtained were encouraging. The study results illustrate the advantage of incorporating a measurement of outdoor air CO_2 concentration with each sensor – offset errors cancel out in the indoor minus outdoor CO_2 concentration difference. For widespread acceptance, it seems likely that the costs of these systems will need to be reduced.

2.4.4 Spatial Variability of CO_2 Concentration in Meeting Rooms

The purpose of the multipoint CO_2 concentration measurements in occupied meeting rooms was to provide information for locating the CO_2 sensors in meeting rooms. The Title 24 standard requires that CO_2 be measured between 0.9 m and 1.8 m (3 feet and 6 feet) above the floor with no less than one sensor per 930 m^2 of floor area. The multipoint measurement results varied among the meeting rooms. In some instances, concentrations at different wall-mounted sample points varied by more than 200 ppm and concentrations at these locations sometimes fluctuated rapidly. These concentration differences may partially be a consequence of the high CO_2 concentrations (for example, 50,000 ppm) in the exhaled breath of nearby occupants. Because the results of the multipoint measurements varied among meeting rooms, this research does not result in definitive guidance for locating sensors in meeting rooms; however, the results suggest that measurements at return-air grilles may be preferred to measurements at wall-mounted locations. In four out of seven data sets, CO_2 concentration at return-grille locations fell between the maximum and minimum of CO_2 concentrations at wall-mounted locations and in five of seven data sets, the period average concentration at return grilles was within 10 percent of the period average concentration measured from sample points on walls.

2.4.5 Overall Findings and Their Implications

Together, the findings from the Iowa Energy Center laboratory studies and current field studies indicate that many CO_2 based demand-controlled ventilation systems will fail to meet the design goals of saving energy while assuring that ventilation rates meet code requirements. Given this situation, one must question whether the current prescriptions for demand-controlled ventilation in the Title 24 standard are appropriate. Given the importance of ventilation and considering the demand-controlled ventilation energy savings potential, technology improvement activities by industry and further research are warranted. Some possible technical options for improving the performance of demand-controlled ventilation are listed below:

- Manufacturers of single-location CO_2 sensors for demand-controlled ventilation applications make technology changes that improve CO_2 sensor accuracy. Sensor costs are likely to increase.
- Users of CO_2 sensors for demand-controlled ventilation applications perform sensor calibrations immediately after initial sensor installation and periodically thereafter. Research is needed to determine if such a protocol would maintain accuracy and whether costs would be acceptable. At present, such calibrations appear to be very rare as facility managers are continuously facing other demands.
- Demand-controlled ventilation systems use existing CO_2 sensors that are more accurate, stable, and expensive than the sensors traditionally used for demand-controlled ventilation. To spread the cost of these sensors, multilocation sampling systems may be necessary. Pilot scale evaluations of this option included in this project are too limited

for conclusions but suggest that these systems may be more accurate. Costs will likely need to be reduced.

- Demand-controlled ventilation systems may be controlled by systems that count occupants, as opposed to by systems that measure CO_2 concentrations. Two optical systems for counting occupants as they pass through doorways were evaluated and the findings are provided in Chapter 4. Other people-counting options may be feasible, such as radio frequency identification that is now used routinely to indicate location of inventories are provide occupants access through normally locked building doors. With further development, people counting systems might be an attractive alternative to CO_2 sensors for demand-controlled ventilation.

It is clear that further research will be necessary to develop and evaluate these technical options. Policy changes, such as changes in aspects of the Title 24 standard pertaining to demand-controlled ventilation, may be an option for stimulating the necessary technology development. Chapter 5 provides recommendations related to prescriptions for demand-controlled ventilation in Title 24.

2.5 Conclusions

The accuracy of single-location CO_2 sensors, as they are applied and maintained for demand-controlled ventilation in commercial buildings, is frequently less than specified in the Title 24 standard and frequently less than needed to meet the design goals of saving energy while assuring that ventilation rates meet code requirements.

The average accuracy of single-location CO_2 sensors varies among manufacturers and is higher with a single lamp single wavelength design. However, use of sensors only from the manufacturer with the best average accuracy or only single lamp single wavelength sensors, while helpful, would not result in widespread compliance with the Title 24 sensor accuracy requirements.

Accuracy varied substantially in each age category and, in general, the association of sensor age with accuracy was not statistically significant. Replacing CO_2 sensors every few years would not result in widespread compliance with the Title 24 sensor accuracy requirements.

Because the results obtained from energy management systems generally agreed well with results obtained from sensor displays, the measurement errors of single-location CO_2 sensors appear to be primarily a consequence of sensor problems and not a consequence of errors in translating the sensor output signals to building energy management systems.

No facility manager indicated that they had calibrated the single-location CO_2 sensors in their facility, after the initial sensor installation and checkout period.

The data from the pilot studies of the accuracy of multilocation monitoring systems are insufficient as a basis for firm conclusions about the accuracy of these systems; however, the limited results obtained were encouraging. For widespread acceptance, it seems likely that system costs will need to be reduced.

Because the results of the multipoint CO_2 concentration measurements varied among meeting rooms, this research does not result in definitive guidance for locating sensors in meeting rooms; however, the results suggest that measurements at return-air grilles may be preferred to measurements at wall-mounted locations.

Changes are needed in technologies used for demand-controlled ventilation. Research and policy changes may be necessary to stimulate the needed technology improvements.

CHAPTER 3: Assessment of Energy Savings Potential from Use of Demand-Controlled Ventilation in General Office Spaces in California

3.1 Background

Most building codes require that a minimum amount of outdoor air be provided to ensure adequate IAQ. To comply, ventilation systems typically are designed to operate with a fixed minimum outdoor air supply rate usually based on design occupancy that is much higher than occupancy levels during most of the time. While measured data on the minimum ventilation rates in existing offices are limited and subject to large measurement error, a survey of 100 U.S. office buildings supported by the U.S. Environmental Protection Agency provides the best available data (Persily and Gorfain 2008). The measurements of ventilation rates in this survey collected when HVAC systems should be supplying minimum amounts of outdoor air were analyzed and indications showed that, on average, minimum ventilation rates dramatically exceed code requirements that are typically 7.1 L/s to 9.4 L/s per occupant depending on occupant density (California Energy Commission 2008). The high measured ventilation rates are partly a consequence of the low average occupant density in offices, relative to the design density, but may also be due to the absence, in most office buildings, of any real-time measurement and feed-back-control system for minimum ventilation rates.

To address the problems of too much or too little outdoor air, the HVAC system can use a demand-controlled ventilation strategy to tailor the amount of outdoor air to the occupancy level. CO_2 sensors have emerged as the primary technology for indirectly monitoring occupancy and implementing demand-controlled ventilation: CO_2 sensors monitor CO_2 levels in the indoor air, and the HVAC system uses data from the sensors to adjust the amount of incoming outdoor air. If the HVAC system has an outdoor air economizer, the ventilation rate will be higher than indicated by the demand-controlled ventilation controlled system when weather is mild.

Under the 2008 California Building Energy Efficiency Standards (Title 24) (California Energy Commission 2008), demand-controlled ventilation is required for a space served by either a single zone system or a multizone system with DDC to the zone level that has an air-side economizer if the design occupant density is greater than or equal to 26.9 people per 100 m^2, with some exceptions. General office spaces are not subject to the Title 24-2008 demand-controlled ventilation requirement; however, given the evidence described above that minimum ventilation rates in offices without demand-controlled ventilation are, on average, much higher than required in codes, a significant energy savings from demand-controlled ventilation was hypothesized especially for the more severe California climates. The purpose of this assessment study was to estimate the energy savings potential and cost effectiveness of demand-controlled ventilation for general office spaces through building performance simulations. The simulations assumed features of a typical medium size office building and were performed for California climate zones that are representative of the coastal, valley, desert, and mountain climate conditions in the State.

Demand-controlled ventilation system energy and environmental benefit overviews, together with typical demand-controlled ventilation design configurations and CO_2 sensor technologies, were well presented by prior documents (Carpenter 1996; Emmerich and Persily 2001; Fisk and de Almeida 1998; Raatschen 1990; Schell et al. 1998). This assessment is different from other demand-controlled ventilation energy savings analysis which used the same design ventilation rates for the base cases as well as the demand-controlled ventilation cases, while this assessment used the actual ventilation rates from two measurement approaches for the base cases, and used the code minimum ventilation rates for the demand-controlled ventilation cases. This assessment serves to capture the boundaries of demand-controlled ventilation life cycle cost savings for office buildings in California under various scenarios, which can be valuable reference to support the adoption of demand-controlled ventilation for office spaces in future versions of Title 24.

3.2 Methods

This assessment modeled the energy impact of demand-controlled ventilation in terms of whole building energy performance which takes into account the integration of and interaction between building components and systems. The DOE commercial building benchmark (Torcellini et al. 2008) for the medium-size office building was selected and adopted based on the U.S. commercial building energy consumption survey (U.S. Energy Information Administration 2003) indicating that office buildings were the most common building type, comprised the largest floor area, and consumed the most energy in the commercial building sector. The energy simulation model was modified to comply with the Title 24-2008 prescriptive requirements, including building envelope insulation level, lighting power level, and HVAC equipment efficiencies. The Title 24 Standards occupancies were used, and demand-controlled ventilation was added to the energy models. The energy usage difference between the base cases without demand-controlled ventilation and the alternative cases with demand-controlled ventilation are equal to the HVAC energy savings due to the use of demand-controlled ventilation. HVAC energy savings include energy savings from cooling, heating, and supply fans.

The source energy use of the building was calculated, based on the electricity use and natural gas use, as follows for all five climate zones (Deru and Torcellini 2007):

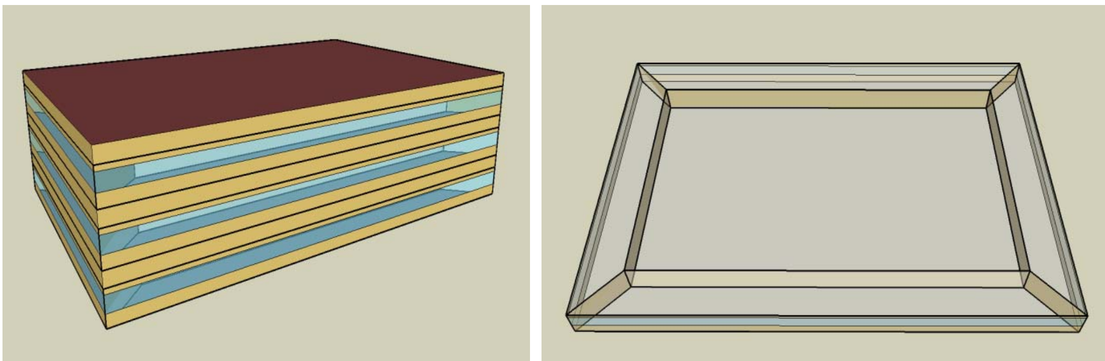
$$\text{Source Energy MJ} = \text{Electricity kWh} * 3.6 * 3.095 + \text{Natural Gas MJ} * 1.092 \quad 3.1$$

where 3.095 and 1.092 are the site-to-source conversion factors for the electricity and natural gas consumption, respectively.

3.2.1 Medium-Size Office Building

The medium size office building has a rectangular shape about 50 m x 33 m (Figure 16). It has three identical stories with a total floor area of 4,982 m^2. Each floor has five thermal zones: four perimeter ones and one core. All five zones are assumed to be general office occupancy. The window-wall-ratio is 33 percent. The building does not have daylighting controls. The building is served by three packaged variable air volume systems with gas furnace for heating. One system serves one floor. Each of the three packaged variable air volume systems has an air-side economizer which provides up to 100 percent of outdoor air for free cooling when indoor and outdoor conditions favor economizer operation.

Figure 16: Three-Dimensional View of the Office Building with Typical Floor Plan



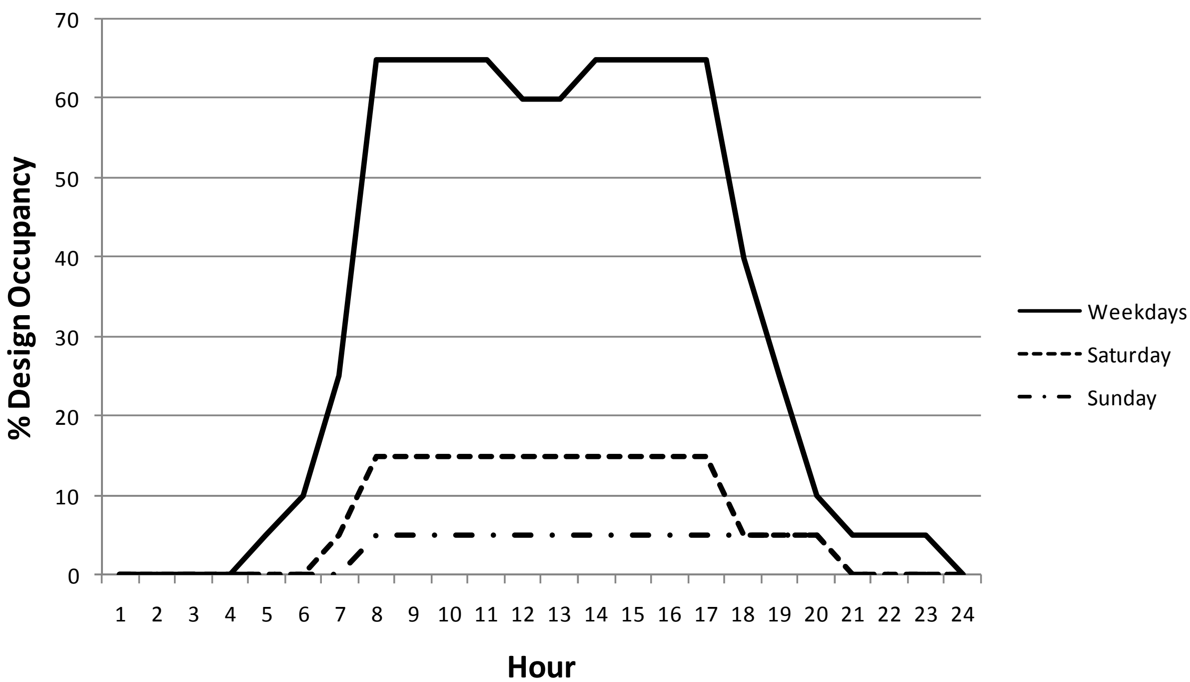
The building size, shape, and operating schedules stay the same for all locations, but the building efficiency level varies with climate zone according to Title 24-2008 prescriptive requirements. Table 8 summarizes the internal loads and minimum ventilation rate for the office building based on the Title 24 Standards.

Table 8: Internal Loads and Minimum Ventilation Rate of Office Buildings

Occupan-cy Type	Design #people per 100 m²	Sensible Heat W/person	Latent Heat W/person	Recepta-cle Load W/m²	Hot Water Load W/person	Light-ing Power W/m²	Ventilation L/s/m²
Office Buildings	10.8	73	60	14.4	31	9.15	0.76

Figure 17 shows the occupant schedules for weekdays and weekends with the percentage values representing the number of occupants in the building divided by the design number of occupants, converted to a percentage. These daily profiles are applicable year round, for example, assuming no seasonal variations.

Figure 17: Occupancy Schedule of Office Building



Five cities representing typical climate regions of California were chosen and are identified in Table 9. The Title 24 Standards weather data for the chosen five climate zones was used in the simulations.

Table 9: Five Typical California Climate Zones

Description	California Climate Zone	Representative City
North Coast	3	San Francisco
South Coast	6	Los Angeles
Central Valley	12	Sacramento
Desert	14	China Lake
Mountains	16	Mt. Shasta

3.2.2 Outdoor Air Ventilation Rates

For the base cases without demand-controlled ventilation, a constant outdoor air flow of 13.2 or 38.2 L/s per occupant was used based on average weekday occupancy when the building is occupied and ventilated. These two values of ventilation rates are based on the measured results from a survey of 100 representative U.S. office buildings and unpublished analyses by the co-author of this report. The survey is the only known U.S. study of ventilation rates and other indoor air quality conditions in a large representative sample of office buildings. Ventilation and HVAC airflow data from this survey are described by Persily and Gorfain (Persily and Gorfain 2008). The survey took place for a broad range of weather conditions and the researchers analyzed data collected when the outdoor air temperature was above 22°C and, consequently, outdoor air supply rates should be at the minimum given the usual economizer control strategy. The resulting 13.2 L/s/person average minimum ventilation rate is based on analyses of peak measured one-hour average carbon dioxide concentrations, assuming that occupants emit 0.0052 L/s of CO_2 and that the measured one-hour peak concentration is 80 percent of the true equilibrium CO_2 concentration. The 38.2 L/s per occupant average minimum ventilation rate is based on use of air velocity sensors to measure outdoor air flow rate, or from the difference between supply and recirculation air flow, both measured using velocity sensors. The two resulting average minimum ventilation rates are very different and, at present, it is not known which value is more accurate.

For the alternative cases with demand-controlled ventilation, the space minimum outdoor air flow was calculated, consistent with the Title 24 Standards, as the larger of:

- 8.3 L/s/person times the current number of occupants present, where the current number of occupants equals the design occupancy multiplied by the occupant schedule percentage shown in Figure 17: Occupancy schedule of office building
- The value of 8.3 L/s per person corresponds to the ventilation rate necessary to maintain indoor carbon dioxide in an office building less than 600 ppm greater than the outdoor concentration assuming a carbon dioxide generation rate per occupant of 0.0052 L/s. This 600 ppm maximum difference between indoor and outdoor concentration is specified for demand-controlled ventilation in Title 24-2008.
- 0.76 L/s/m² times the space floor area.

An average occupancy that is 50 percent of design occupancy was selected for the simulations to match typical practice in office buildings (Figure 17: Occupancy schedule of office building

The 50 percent average weekday occupancy was used together with the two base case ventilation rates (13.2 or 38.2 L/s per occupant) to set the constant minimum ventilation air flow for the base case simulations. For the demand-controlled ventilation cases, the CO_2 demand-controlled ventilation system increased outdoor air ventilation rates when occupancy is at a higher level. The demand-controlled ventilation energy savings potential is a consequence of its ability to match the outdoor air ventilation rate with actual occupancy, which is often less than peak design occupancy. With a design occupant density of 10.8 people/100 m² for office buildings, the design outdoor air flow based on the per person requirement is the larger of 0.76 L/s/m² and a time varying rate that is always less than or equal to 0.89 L/s/m² (8.3 L/s/person X 10.8 people/100 m²). Two alternate design occupancy levels representing a 50 percent and a 100 percent higher occupancy are included in the analysis. Table 10 summarizes the minimum outdoor air supply rates for all cases.

For both the base cases and the demand-controlled ventilation cases, the packaged variable air volume systems have air side economizers as required by the Title 24 Standards. Therefore, the actual outdoor air flow can exceed the minimum ventilation rate when economizers operate.

Table 10: Minimum Outdoor Air Requirement

Case Description	Design Occupant Density #people per 100 m²	Weekday Average Occupant Density # people per 100 m²	Design OA L/s/m² based on 13.2 L/s/p in base cases or 8.3 L/s/p in DCV cases	Design OA L/s/m² based on 38.2 L/s/p in base cases or 8.3 L/s/p in DCV cases	Title 24 Required Minimum OA L/s/m²	Actual OA Supply L/s/m²
Base Cases	10.8	5.4	0.71	2.03	NA	0.71 or 2.03
	16.1	8.0	1.07	3.10	NA	1.07 or 3.10
	21.5	10.8	1.42	4.11	NA	1.42 or 4.11
DCV* Cases	10.8	5.4	0.89 (weekday avg. = 0.088)	0.89 (weekday avg. = 0.088)	0.76	Varies with time (0.76 to 0.89)
	16.1	8.0	1.34 (weekday avg. = 0.132)	1.34 (weekday avg. = 0.132)	0.76	varies with time (0.76 to 1.34)
	21.5	10.8	1.79 (weekday avg. = 0.176)	1.79 (weekday avg. = 0.176)	0.76	varies with time (0.76 to 1.79)

*DCV = demand-controlled ventilation

3.2.3 Simulation Tool

EnergyPlus version 3.0, released in November 2008, was used to simulate the whole building energy performance of the selected medium size office building. The demand-controlled ventilation algorithm implemented in EnergyPlus 3.0 is based on the calculation of space minimum outdoor air requirements for varying number of occupants and a constant component based on space floor area. EnergyPlus 3.0 calculates the system-level outdoor air requirement as the sum of space outdoor air flows, without considering zone air distribution effectiveness or system ventilation efficiency as required by ASHRAE standard 62.1-2007 (ASHRAE 2007). This calculation works fine for single zone systems or multizone systems serving zones with same design occupancy and schedule. In this assessment, all spaces are assumed to be general offices with same design occupancy and schedule.

3.2.4 Cost Estimates

In the demand-controlled ventilation measure analysis (Taylor Engineering 2002) for the development of Title 24-2005, the demand-controlled ventilation cost for a single zone system was estimated to be $575 which included parts and labor. Adjusted for inflation and multiple zones served by a packaged variable air volume system, the demand-controlled ventilation cost for each of the three PVAV systems were estimated to be $3,085 (average $617 per zone X 5 zones). The demand-controlled ventilation cost is $1.86/m² on a per building conditioned floor area basis.

Based on a 15 year life cycle and 3 percent discount rate for an installed demand-controlled ventilation system, the present value (PV) of energy costs were estimated to be $1.37/kWh for electricity and $0.069/MJ for natural gas in California (Eley Associates and New Building Institute 2002). These present values cost numbers were multiplied by the changes in annual energy consumption in the estimation of the present value of cost savings for the 15-year life cycle.

3.3 Results

Table 11 summarizes the simulation results and calculated energy usage and costs savings. The Design OA column lists the equivalent outdoor air rate per floor area converted from the outdoor air rate per occupant. The next three columns show the whole building annual energy use per conditioned floor area. The remaining columns indicate the energy and cost savings for demand-controlled ventilation relative to the base cases.

Table 11: Calculated Annual Energy Usage and Net Present Value of Costs Savings

Location	Design Occupant Density #people/100 m²	Cases	Design OA L/s/m²	Building Electricity Use kWh/m²	Building Gas Use MJ/m²	Building Source Energy MJ/m²	Building Source Energy Savings %	HVAC Energy Cost PV $/m²	HVAC Energy Cost Savings PV $/m²	DCV Cost $/m²	DCV Life Cycle Cost Savings NPV $/m²
CZ 3	10.8	Base Case I (13.2 L/s/person)	0.71	124.3	29.3	1448	-0.1%	58.92	-0.18	1.86	-2.03
		Base Case II (38.2 L/s/person)	2.03	124.9	32.8	1459	0.7%	60.08	0.98	1.86	-0.88
		DCV	0.89	124.4	30.4	1450	n.a.	59.10	n.a.	n.a.	n.a.
	16.1	Base Case I (13.2 L/s/person)	1.07	127.7	28.8	1487	0.1%	63.64	0.17	1.86	-1.68
		Base Case II (38.2 L/s/person)	3.10	131.1	32.4	1529	2.9%	68.53	5.07	1.86	3.21
		DCV	1.34	127.7	27.7	1485	n.a.	63.46	n.a.	n.a.	n.a.
	21.5	Base Case I (13.2 L/s/person)	1.42	131.3	28.1	1526	0.2%	68.45	0.26	1.86	-1.60
		Base Case II (38.2 L/s/person)	4.11	138.8	33.4	1617	5.8%	79.09	10.90	1.86	9.04
		DCV	1.79	131.2	26.7	1523	n.a.	68.19	n.a.	n.a.	n.a.
CZ 6	10.8	Base Case I (13.2 L/s/person)	0.71	137.2	23.5	1589	-0.1%	76.28	-0.25	1.86	-2.11
		Base Case II (38.2 L/s/person)	2.03	138.4	24.1	1603	0.7%	77.91	1.38	1.86	-0.48
		DCV	0.89	137.4	23.6	1591	n.a.	76.53	n.a.	n.a.	n.a.
	16.1	Base Case I (13.2 L/s/person)	1.07	141.6	21.9	1637	0.0%	82.10	0.07	1.86	-1.79
		Base Case II (38.2 L/s/person)	3.10	144.1	22.7	1666	1.8%	85.57	3.55	1.86	1.69
		DCV	1.34	141.5	21.8	1636	n.a.	82.03	n.a.	n.a.	n.a.
	21.5	Base Case I (13.2 L/s/person)	1.42	145.9	20.9	1686	0.1%	88.02	0.20	1.86	-1.66
		Base Case II (38.2 L/s/person)	4.11	152.2	22.6	1758	4.2%	96.68	8.85	1.86	6.99
		DCV	1.79	145.8	20.6	1684	n.a.	87.82	n.a.	n.a.	n.a.
CZ 12	10.8	Base Case I (13.2 L/s/person)	0.71	135.9	30.7	1582	-0.5%	74.99	-0.78	1.86	-2.63
		Base Case II (38.2 L/s/person)	2.03	138.8	42.2	1627	2.3%	79.65	3.89	1.86	2.03
		DCV	0.89	136.4	33.4	1590	n.a.	75.76	n.a.	n.a.	n.a.
	16.1	Base Case I (13.2 L/s/person)	1.07	140.4	32.7	1635	0.3%	81.30	0.55	1.86	-1.31
		Base Case II (38.2 L/s/person)	3.10	144.5	41.9	1692	3.7%	87.56	6.81	1.86	4.95
		DCV	1.34	140.1	30.6	1630	n.a.	80.75	n.a.	n.a.	n.a.
	21.5	Base Case I (13.2 L/s/person)	1.42	144.8	35.3	1688	0.7%	87.40	1.16	1.86	-0.70
		Base Case II (38.2 L/s/person)	4.11	151.3	43.2	1771	5.4%	96.95	10.71	1.86	8.85
		DCV	1.79	144.1	30.9	1676	n.a.	86.24	n.a.	n.a.	n.a.
CZ 14	10.8	Base Case I (13.2 L/s/person)	0.71	141.8	33.2	1652	-0.4%	83.22	-0.48	1.86	-2.34
		Base Case II (38.2 L/s/person)	2.03	146.6	52.7	1728	4.0%	91.17	7.47	1.86	5.61
		DCV	0.89	141.9	37.9	1658	n.a.	83.69	n.a.	n.a.	n.a.
	16.1	Base Case I (13.2 L/s/person)	1.07	146.5	35.5	1707	0.6%	89.78	1.31	1.86	-0.55
		Base Case II (38.2 L/s/person)	3.10	153.3	52.7	1804	6.0%	100.33	11.86	1.86	10.00
		DCV	1.34	145.5	35.2	1696	n.a.	88.47	n.a.	n.a.	n.a.
	21.5	Base Case I (13.2 L/s/person)	1.42	151.4	42.0	1770	1.5%	96.95	2.85	1.86	0.99
		Base Case II (38.2 L/s/person)	4.11	160.8	54.2	1891	7.8%	110.66	16.56	1.86	14.70
		DCV	1.79	149.6	35.6	1743	n.a.	94.10	n.a.	n.a.	n.a.
CZ 16	10.8	Base Case I (13.2 L/s/person)	0.71	127.9	59.4	1522	-0.3%	65.98	0.21	1.86	-1.64
		Base Case II (38.2 L/s/person)	2.03	128.9	113.0	1592	4.1%	71.11	5.34	1.86	3.48
		DCV	0.89	127.2	70.9	1526	n.a.	65.76	n.a.	n.a.	n.a.
	16.1	Base Case I (13.2 L/s/person)	1.07	131.1	69.7	1569	1.0%	71.06	1.60	1.86	-0.25
		Base Case II (38.2 L/s/person)	3.10	133.2	118.0	1645	5.6%	77.26	7.80	1.86	5.94
		DCV	1.34	130.1	66.0	1554	n.a.	69.46	n.a.	n.a.	n.a.
	21.5	Base Case I (13.2 L/s/person)	1.42	134.5	87.7	1627	2.1%	76.90	2.96	1.86	1.11
		Base Case II (38.2 L/s/person)	4.11	138.5	124.1	1713	7.0%	85.03	11.10	1.86	9.24
		DCV	1.79	133.3	68.6	1592	n.a.	73.94	n.a.	n.a.	n.a.

Figure 18 to Figure 20 show demand-controlled ventilation life cycle cost savings in net present value (NPV) $/m² for the three design occupancy levels.

Figure 18: Demand-Controlled Ventilation Life-Cycle Cost Savings with Design Occupancy of 10.8 People / 100 M^2 and Base Case Minimum Ventilation Rates of 13.2 L/s or 38.2 L/s per Person

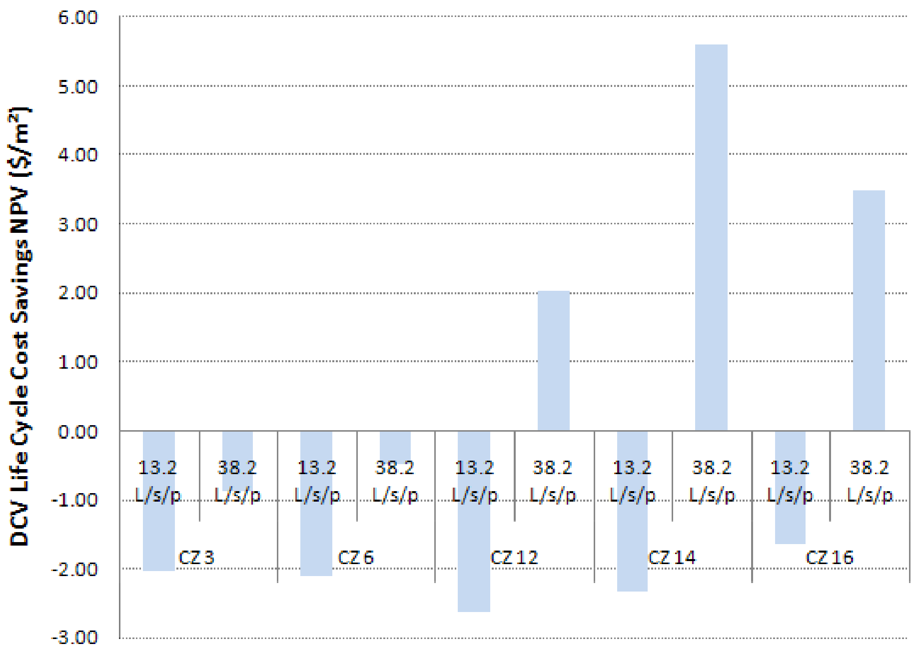


Figure 19: Demand-Controlled Ventilation Life-Cycle Cost Savings with a Design Occupancy of 16.1 People / 100 M^2 and Base Case Minimum Ventilation Rates of 13.2 or 38.2 L/s per Person

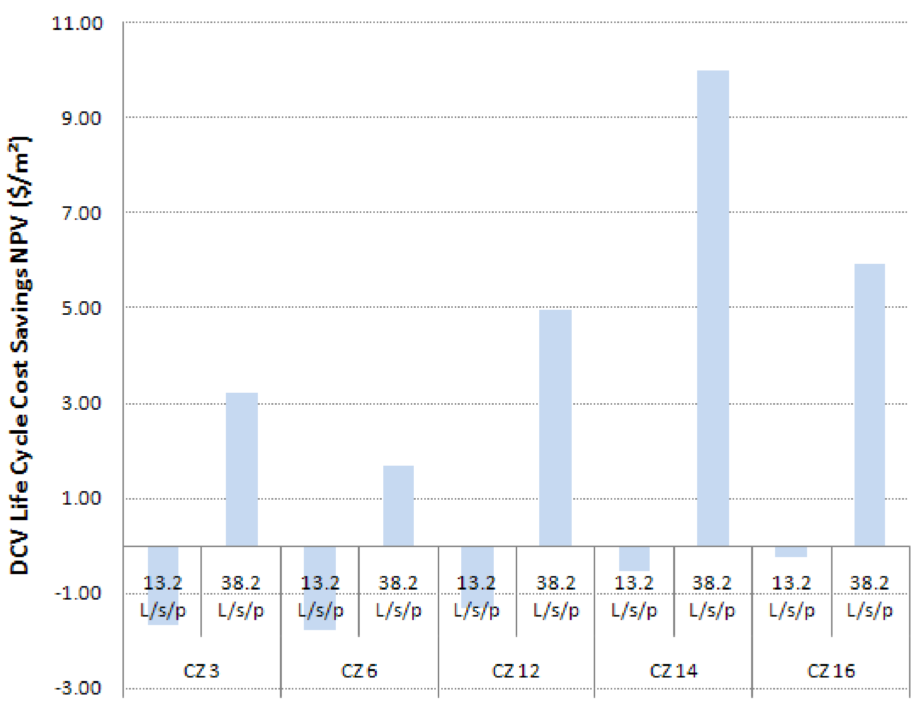
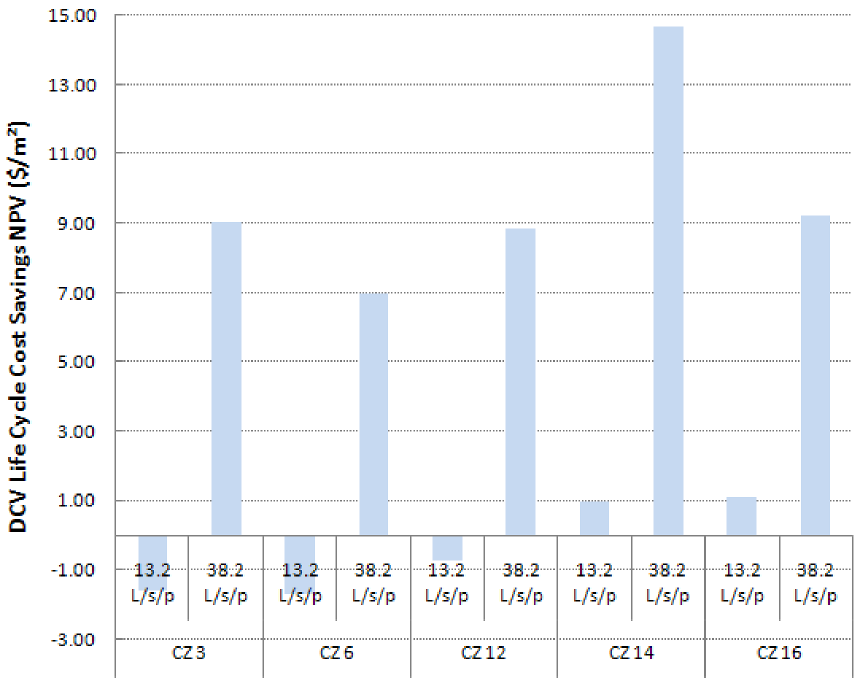


Figure 20: Demand-Controlled Ventilation Life-Cycle Cost Savings with a Design Occupancy of 21.5 People / 100 M^2 and Base Case Minimum Ventilation Rates of 13.2 or 38.2 L/s per Person



From Figure 18 through Figure 20, it can be seen that with the reference outdoor ventilation rate of 13.2 L/s/person, only for climate zones 14 and 16 do the calculations indicate a marginal life cycle cost savings for demand-controlled ventilation when the design occupancy is at 21.5 people per 100 m^2. This marginal life cycle cost savings is probably due to the fact that the demand-controlled ventilation cases have higher design ventilation rates than the cases without demand-controlled ventilation at a fixed ventilation rate of 13.2 L/s/person for all three occupant density levels. For the base case with a reference ventilation rate of 38.2 L/s/person, the cases without demand-controlled ventilation always have higher ventilation rates than the demand-controlled ventilation cases for all three occupant density levels.

Figure 18 at design occupancy of 10.8 people per 100 m^2, demand-controlled ventilation is cost effective (positive NPV savings) with the reference outdoor ventilation rate of 38.2 L/s/person for climate zones 12, 14, and 16. The largest estimated savings is \$5.62/m^2 in climate zone 14, followed by \$3.49/m^2 in climate zone 16, and \$2.03/m^2 in climate zone 12.

From Figure 19 at design occupancy of 16.1 people per 100 m^2, demand-controlled ventilation is cost effective with the reference outdoor ventilation rate of 38.2 L/s/person in all five climate zones, with the largest savings of NPV \$10.0/m^2 in climate zone 14, followed by \$5.94/m^2 in climate zone 16, \$4.95/m^2 in climate zone 12, \$3.22/m^2 in climate zone 3, and \$1.69/m^2 in climate zone 6. The savings are much higher than those at design occupancy of 10.8 people per 100 m^2.

From Figure 20 at design occupancy of 21.5 people per 100 m^2, demand-controlled ventilation is cost effective with the reference outdoor ventilation rate of 13.2 L/s/person in climate zones 3, 6, and 12. The largest savings with the reference outdoor ventilation rate of 38.2 L/s/person is NPV \$14.7/m^2 in climate zone 14, followed by \$9.24/m^2 in climate zone 16, \$9.04/m^2 in climate zone 3, \$8.85/m^2 in climate zone 12, \$7.00/m^2 in climate zone 6. The savings are much higher than those at design occupancy of 16.1 people per 100 m^2.

The largest estimated demand-controlled ventilation life cycle cost savings and energy savings occur for climate zone 14 (desert) --this is due to the significant heating demand in winter and cooling in summer. For cooling dominant climates like climate zone 6 (south coast), the demand-controlled ventilation savings mostly come from the reduction of outdoor air cooling during summer, while for heating dominant climates like climate zone 16 (mountains), the demand-controlled ventilation savings mostly come from the reduction of outdoor air heating during winter

Figure 18 through Figure 20 does not show the base case minimum ventilation rates above which demand-controlled ventilation become cost effective. To determine these pivot minimum ventilation rates under the Title 24 occupant density of 10.8 people per 100 m^2, two more base case ventilation rates were studied for each of the five climate zones. Table 12 summarizes the simulation results and the calculated pivot minimum ventilation rates using quadratic curve fit for the data points. Using the quadratic curve fit and the Title 24 Standards office occupancies, the demand-controlled ventilation becomes cost effective when the base case minimum ventilation rate is greater than 42.5, 43.0, 24.0, 19.0, and 18.0 L/s per person for climate zone 3, 6, 12, 14, and 16 respectively.

Table 12: Determination of Base Case Minimum Ventilation Rates Above Which Demand-Controlled Ventilation Become Cost-Effective With Title 24 Occupant Density of 10.8 People Per 100 M^2

Climate Zone	Base Case Minimum OA (L/s/person)	Life Cycle Cost Savings NPV $/m²	Base Case Minimum Ventilation Rates (L/s/person) Above Which Demand-Controlled Ventilation Become Cost Effective
CZ 3	13.2	-2.03	42.5
	25.5	-1.50	
	38.2	-0.88	
	47.1	0.84	
CZ 6	13.2	-2.11	43.0
	25.5	-1.19	
	38.2	-0.48	
	47.1	0.36	
CZ 12	13.2	-2.63	24.0
	20.7	-0.69	
	30.2	1.01	
	38.2	2.03	
CZ 14	13.2	-2.34	19.0
	20.7	0.47	
	30.2	3.87	
	38.2	5.61	
CZ 16	13.2	-1.64	18.0
	20.7	0.60	
	30.2	2.84	
	38.2	3.48	

3.4 Discussion

This analysis has estimated the energy and life cycle cost impacts of using demand-controlled ventilation in general office spaces in various California climate zones. For reference, when demand-controlled ventilation was not employed the fixed minimum outdoor air ventilation rate was assumed to equal 13.2 L/s or 38.2 L/s per occupant. Three design occupant densities were employed; however, per the occupancy schedule in Figure 17, the actual peak occupant density was only 65 percent of the design occupant density. The analyses indicate the potential for significant energy and life-cycle cost savings from demand-controlled ventilation in general office spaces if the base case fixed ventilation rate without demand-controlled ventilation is 38.2 L/s per occupant. While this ventilation rate comes from measured survey data, a much lower rate of 13.2 L/s per occupant is derived from the same survey based on application of a different measurement method. With this lower reference ventilation rate, the modeling indicates that demand-controlled ventilation is not cost effective except in the most severe California climates and in buildings with a high design occupant density of 21.5 persons per 100 m^2. Unfortunately, it is not known which of these estimates of base case ventilation rates without demand-controlled ventilation is more accurate. Also, the survey that yielded the ventilation rate data is from buildings throughout the U.S., while data from a representative survey of California office buildings would serve as a better reference. Measuring accurate minimum ventilation rates in typical existing California office buildings is a multiyear project, and is a good candidate for future research.

While the main source of uncertainty is the base case ventilation rate as described above, other sources of uncertainty should be mentioned. The analysis was performed for the prototypical office building and results would vary somewhat with building size and features. Demand-controlled ventilation capital costs and future energy costs are uncertain. If current energy-cost inflation trends continue, the demand-controlled cost effectiveness ventilation may improve over time. Energy prices have been increasing faster than the general inflation rate (U.S. Census Bureau 2009). While cost trends have not been identified for the CO_2 sensors used in demand-controlled ventilation, it is suspected that the cost increase of mass produced electronic equipment is less than the general inflation rate. The EnergyPlus program used for the modeling computes the ventilation rates in buildings with demand-controlled ventilation based on the number of occupants present in the building while actual demand-controlled ventilation systems respond to the indoor concentration of occupant-generated CO_2 which lags in time behind occupancy. The projected energy savings would probably only be modestly larger if EnergyPlus modeled demand-controlled ventilation based on occupant-generated CO_2.

3.5 Conclusions

In California climates, demand-controlled ventilation in general office spaces is expected to save significant energy and be cost effective only if typical ventilation rates without demand-controlled ventilation are very high relative to the minimum rate required in codes. Under the Title 24 Standards office occupancy, demand-controlled ventilation becomes cost effective when the base case minimum ventilation rate is greater than 42.5, 43.0, 24.0, 19.0, and 18.0 L/s per person for climate zones 3, 6, 12, 14, and 16 respectively. Until the large uncertainties about ventilation rates without demand-controlled ventilation are reduced, the case for requiring demand-controlled ventilation in general office spaces will be a weak case.

CHAPTER 4: Optical People Counting for Demand-Controlled Ventilation – A Pilot Study of Counter Performance

4.1 Background

An alternative to using CO_2 sensors to provide the control signal for demand-controlled ventilation is to count the number of people who enter and exit a building or section of a building and use the net count of people in the building or building section as an input to the ventilation rate control system. This document discusses pilot-scale evaluations of the accuracy of two people counting systems potentially usable for this application. This people counting system evaluation is motivated, in part, because the CO_2 sensors typically used for demand-controlled ventilation frequently have large measurement errors (Fisk et al. 2009). In theory, discrete event counting, such as detecting people movements through a building space, may be less subject to errors, unlike CO_2 concentration measurement sensors whose performance can degrade over time.

There are advantages and disadvantages to using people counting systems compared to using CO_2 sensors-based systems for demand-controlled ventilation. Advantages include faster time response – people counters respond immediately while CO_2 concentrations adjust over periods of minutes to hours after changes in occupancy. However, the delay in detecting occupancy with CO_2 sensors is sometimes considered desirable as CO_2-based demand-controlled ventilation systems respond to a proxy for the indoor concentration of occupant-generated pollutants, which is what the demand-controlled ventilation is designed to control. If desired, software can be used to add a lag in the response times for occupancy-based demand-controlled ventilation systems. Another advantage of people counting is that its performance is not subject to errors caused by the exhaled breath of people. The high CO_2 levels in exhaled breath of people located near a CO_2 sensor can cause the sensor to respond to a localized elevated CO_2 concentration as opposed to a room average CO_2 concentration. A disadvantage of people counting is that it must be accompanied by a system for measuring the outdoor air flow rate provided by the building's heating, ventilating, and air conditioning (HVAC) system. Accurate measurement of outdoor air flow rates is often very challenging (Fisk et al. 2006). CO_2 sensors are often used for demand-controlled ventilation without having any measurement system for the outdoor air flow rate, although, in such applications, the HVAC system may be unable to accurately provide the minimum outdoor air supply per unit floor area specified in the applicable ventilation standard. Another disadvantage of people counting for demand-controlled ventilation is that a larger number of people counters than CO_2 sensors may be necessary in small- to medium-sized meeting rooms with multiple doors. A people counter is required at each door while only a single CO_2 sensor may be needed. Finally, for accuracy, people counters require a small zone near the door in which occupants do not sit or stand, while CO_2 sensors are not subject to this restriction.

An optical people counting system for demand-controlled ventilation is a new technology. This project evaluated one product that was designed primarily for other applications, such as counting people entering a retail store for market-related purposes. Another technology evaluated was a prototype that is not yet available commercially. Consequently, this technology is likely to evolve and improve and its costs may decrease if production rates increase.

4.2 Methods

People Counting System number 1 (PCS1) uses thermal sensors (called cameras in installation literature), other electronics, and software to detect the movements of a warm human body in a field of view. Multiple sensors can be interconnected into an integrated counting system. The count of people passing through the field of view in both directions (such as, in-count and out-count) is communicated to a connected computer system. In addition, low resolution thermal images of the moving people, insufficient for identification of individuals, can be viewed. Sensors with different fields of view, represented by 20^o, 40^o, and 60^o view angles are available, with the wider view versions designed for installation closer to the floor. Per the manufacturer's literature and discussions with the manufacturer, PCS1 is best suited for applications in which the sensor's installation height is at 3.5 m for a sensor with a 60^o view, which is the sensor version chosen for testing. The minimum recommend height for the 60^o sensor is 3.05 m (10 ft.). Sensor heights can be as large as 8.23 m for a sensor with a 20 degree view. Individual sensors can detect passage of people through 0.91 m to 3.05 m wide entrances. The sensor is to be installed indoors. The cost paid for the hardware used at a single door entrance was $1,450 and the hardware cost for the multi-door entrance was $3,400.

People Counting System Number 2 (PCS2) uses sensors, other electronics, and software to detect the movements of people through a doorway. A detailed description of the system operation principles was not available. Multiple people counters can be interconnected into an integrated counting system. The count of people in the room increases when a person enters and decreases when a person exits and is communicated to a connected computer system via the BACnet communication protocol. Each counter has two closely spaced sensors. Normally, the counter increases or decreases the total count by full person-units; however, in some situations the total count may increase or decrease by a half person (presumably when only one sensor detects movement). Using software, settings can be modified to optimize counting for different applications. For example, one setting affects how long the person needs to be detected and another affects the size of the person required before the count is incremented. These can be adjusted from baseline settings if people are expected to move very rapidly through a doorway or if children, as opposed to larger adults, are to be counted. Other settings enable or disable half-counts or disallow or enable the sensor's accumulated count to become negative. Per the manufacturer's literature, the sensors for PCS2 are only for use on interior doors 0.81 to 0.91 m wide with a normal, for example, 2.0 m height. The counter is installed above the center of the door, on the side of the door opposite the zone of the door swing. The height of the installed counter should be 2.13 to 2.44 m. The evaluated version of PCS2 was a prototype undergoing beta testing. As a commercial product is not yet available, product cost was not available.

PCS1 was evaluated when installed at a single-door entrance to a laboratory, at the two-door entrance to a conference room, and at a four-door-wide entrance to an office building. The total entrance width of the system of four doors was 4.8 m. A single thermal sensor was employed at the interior door entrances and two interconnected thermal sensors were employed at the four door building entrance. The installed sensor heights were as follows: 3.05, 3.10, 3.35, and 3.58 m at the single-door entrance to the laboratory, 3.5 m at the two-door entrance to a conference room, and 3.12 m at the four-door entrance to the office building. The software allows the user to change some line locations in the field of view that must be crossed by the moving thermal image of a person to create an in-count or out-count. The line positions were adjusted to maximize counting accuracy as people moved through the entrance during initial system checkouts. For example, at the two-door entrance to the conference room most occupants turned left immediately after entering the room and the lines were adjusted to improve counting of people passing through a zone to the left of the doors.

PCS2 was evaluated when installed in accordance with the manufacturers' installation guidance at a single-door entrance of three rooms. Because the system was not intended for use at building entrance doors, no such tests were performed. The door widths were 0.91 m in all cases. Door heights were 2.10 to 2.16 m and the sensor base was approximately 5 cm above the top of the door. Only a single counter, not an integrated system of counters, was evaluated.

The evaluations assessed the accuracy of people counting used visual observations of people movement and record keeping to provide the reference counts. The evaluations included controlled people counting system challenges using preplanned occupant movements through doorways and, in addition, evaluations of counting accuracy when naïve occupants (for example, occupants unaware of the counting system) passed through the entrance doors of the building or room. The controlled challenges are identified in Table 13. Some of the controlled challenges were highly demanding and may infrequently be encountered in practice. There were a few time periods when the person evaluating the systems were uncertain of actual people counts and data from these time periods were not utilized.

In the first controlled PCS2 evaluation at the entrance door to Conference Room 1 and during its use in Conference Room 1 to count naïve occupant movement through the door, the start threshold was set at 100, which was the preprogrammed setting when the unit arrived from the manufacturer. After discussing the initial test results with the manufacturer, the start threshold was set to 300 which is the normal default setting per the manufacturer. Thus, the controlled tests in Room 3 and the evaluations of counting naïve occupant passage through the Conference Room 2 door were performed with the start threshold set at 300. This threshold affects the size of person required to trigger the counter with the setting of 100 better enabling the system to detect children and the setting of 300 normally used to detect adults. Other settings (for example, event = 300, cross = 50) remained throughout the study with the default values preprogrammed in PCS2.

4.3 Results

4.3.1 People Counting System Number 1

Table 13 provides a compilation of counting accuracy results with controlled PCS1 challenges at the single-door entrance to a laboratory. There were no counting errors when single persons walked through the door at a normal or very fast pace except when carrying an open or covered coffee cup containing hot water heated within the last few minutes to the boiling point or wearing a room temperature heavy winter coat with hood covering the head and with the person's hands in the coat pockets. Carrying a cup of hot water resulted in frequent over counting (for example, the measured count was two when the correct count was one) while carrying a warm laptop computer held flat to the floor resulted in no errors. Wearing the room temperature winter coat resulted in frequent under counting, for example, some of those who passed through the door were not counted. There were no counting errors when two persons walked through the door side-by-side but not touching each other; however, if one person had their arm over the shoulder of the other person the system sometimes produced an undercount. When two people walked through the door with the second closely following the first, there were no counting errors, but with three or five persons walking through the door in very close succession, there were some counting errors.

Table 14 provides the results of a very similar set of tests with controlled challenges of PCS1 at the four-door entrance to an office building. The results are qualitatively similar to those of the tests from the single-door entrance of the laboratory except there was some undercounting when single persons exited through the door system at a normal or very fast pace.

Table 13: Results of Controlled Tests of PCS1 at a Single Interior Door Entrance to a Laboratory, Numbers Are Averages of Three Repeated Challenges

Test Conditions	Sensor Height (m)	Cor-rect Count	Entrances Through Door		Exits Through Door		Entran-ces or Exits
			Avg. Count	Count - ing Error (%)	Avg. Count	Count -ing Error (%)	Count-ing Error (%)
single person walks through at a normal pace	3.05	1	1	0	1	0	0
	3.10	1	1	0	1	0	0
	3.35	1	1	0	1	0	0
	3.58	1	1	0	1	0	0
single person walks through at a very fast pace	3.05	1	1	0	1	0	0
	3.10	1	1	0	1	0	0
	3.35	1	1	0	1	0	0
	3.58	1	1	0	1	0	0
single person walks through at a normal pace with covered coffee cup	3.05	1	1.67	67	1.67	67	67
	3.10	1	2	100	1.33	33	67
	3.35	1	1.67	67	1	0	33
	3.58	1	1.67	67	1	0	33
single person walks through at a normal pace with open coffee cup	3.05	1	1.67	67	2	100	83
	3.10	1	2	100	1.67	67	83
	3.35	1	1.67	67	1	0	33
	3.58	1	1	0	1	0	0
single person walks through at a normal pace with a room temperature winter coat with hood on and hands in pockets	3.05	1	1	0	0.67	-33	-16
	3.10	1	1	0	1	0	0
	3.35	1	0.67	-33	0.33	-67	-50
	3.58	1	0.33	-67	0	-100	-83
single person walks through at a normal pace, with a winter coat from the freezer, with hood on and hands in pockets	3.05	1	1	0	1	0	0
	3.10	1	1	0	1	0	0
	3.35	1	1	0	1	0	0
	3.58	1	1	0	1	0	0
single person walks through at a normal pace, with a warm laptop computer held flat to the ground	3.05	1	1	0	1	0	0
	3.10	1	1	0	1	0	0
	3.35	1	1	0	1	0	0
	3.58	1	1	0	1	0	0
two people walk through at a normal pace, side by side, not touching	3.05	2	2	0	2	0	0
	3.10	2	2	0	2	0	0
	3.35	2	2	0	2	0	0
	3.58	2	2	0	2	0	0
two people walk through at a normal pace, side by side, arm over shoulder	3.05	2	2	0	2	0	0
	3.10	2	1.67	-17	2	0	-8
	3.35	2	1.67	-17	2	0	-8
	3.58	2	1.67	-17	1.67	-17	-17
two people walk through at a normal pace, second person follows first as close as comfortable	3.05	2	2	0	2	0	0
	3.10	2	2	0	2	0	0
	3.35	2	2	0	2	0	0
	3.58	2	2	0	2	0	0
three people walk through at a normal pace, one after another as close as comfortable	3.05	3	3.33	11	3	0	6
	3.10	3	3	0	3	0	0
	3.35	3	3	0	3	0	0
	3.58	3	3	0	2.67	-11	-6
five people walk through at a normal pace, one after another as close as comfortable	3.05	5	5	0	4.33	-13	-7
	3.10	5	4.33	-13	5	0	-7
	3.35	5	4.33	-13	4.33	-13	-13
	3.58	5	5	0	3.67	-26	-13

Table 14: Results of Controlled Tests of PCS1 System at a Four-Door Entrance of an Office Building

	Entrances Through Door		Exits Through Door		Entrances or Exits	
Test Conditions	**Num-ber**	**Counting Error (%)**	**Num-ber**	**Counting Error (%)**	**Num -ber**	**Counting Error (%)**
single person walks through at a normal pace	12	0	12	-8	24	4
single person walks through at a very fast pace	12	0	12	-17	24	8
single person walks through at a normal pace with covered coffee cup. (lid temperature 62 ^{o}C [143 ^{o}F])	12	33	12	0	24	21
single person walks through at a normal pace with open coffee cup. (coffee temperature 78 ^{o}C [173 ^{o}F])	12	17	12	8	24	13
single person walks through at a normal pace with a room temperature winter coat with hood on and hands in pockets, hands briefly out to open door	12	-8	12	-42	24	33
single person walks through at a normal pace, with a winter coat from the freezer, with hood on and hands in pockets, hands briefly out to open door (coat surface temperature 2 ^{o}C [36 ^{o}F])	12	33	12	-33	24	42
single person walks through at a normal pace, with a warm laptop held flat to the ground (laptop surface temperature 30 ^{o}C [86 ^{o}F])	12	33	12	0	24	42
two people walk through at a normal pace, side by side, not touching	24	0	24	0	48	21
two people walk through at a normal pace, side by side, arm over shoulder	24	-21	24	-21	48	25
two people walk through at a normal pace, second person follows first as close as comfortable	24	17	24	17	48	17
three people walk through at a normal pace, one after another as close as comfortable	36	19	36	-4	72	14
five people walk through at a normal pace, one after another as close as comfortable	60	10	60	8	120	14

The counting accuracy of naïve occupant passage through the lightly-used two-door of a conference room over multiple days of use is indicated by the numbers in Table 15. In this application, counting errors were less than 10 percent for the total number of people who entered or exited through the door. However, when the net change in indoor occupancy was small (for example, 15 occupants) the percentage error in counting of net change in occupancy could be high (46 percent) although the absolute error were still modest (for example, 7 occupants).

Table 15: Counting Accuracy of PCS1 System with Naïve Occupants Passing Through a Two-Door Entrance to a Conference Room

Entrance Through Door (s)			Exit Through Door (s)			Entrances Minus Exits		
Actual	Counted	Error	Actual	Counted	Error	Actual	Counted	Error
53	57	7.5%	68	65	-4.4%	-15	-8	7 (-46%)

The accuracy of counting of naive occupant passage through the four-door entrance of the office building is indicated by the numbers in Table 16. Because accuracy appeared to be reduced when the floor below the thermal sensors was illuminated and heated by sunlight, data were compiled for time periods with and without impingement of direct sunlight (determined visually) on the floor beneath the sensors. With no direct sunlight impinging on the floor, the errors in counting the number of people who entered or exited through the door were 13 percent or less. With direct sunlight on this section of floor, these errors were as high as 26 percent. As in the single door installation, when the net change in indoor occupancy was small the percentage error in counting of net change in occupancy was high (54 percent).

Table 16: Counting Accuracy of PCS1 System with Naïve Occupants Passing Through a Four-Door Entrance to an Office Building

Sunlight*	Entrance Through Doors			Exit Through Doors			Entrances minus Exits		
	Actual	Counted	Error	Actual	Counted	Error	Actual	Counted	Error
No	149	168	13%	180	194	8%	-31	-26	5 (-16%)
Yes	110	81	-26%	75	65	-13%	35	16	-19 (-54%)

* Direct sunlight impinging on floor beneath thermal sensors

4.3.2 People Counting System Number 2

Table 17 provides a compilation of PCS2 counting accuracy results with controlled challenges at the single-door entrance to Conference Room 1. There were no counting errors when single persons walked through the door at a normal pace, even when carrying cups of hot coffee or warm laptop computers. The counter failed to detect people wearing a room temperature winter coat with hood over their head and their hands in the pockets, but detected people without error when the winter coat had just been removed from a freezer. When a single person walked through the door at a very fast pace, the counter failed to register a count 25 percent of the time. When two people walked side-by-side through the door simultaneously, the counter normally registered only a one-person change in count. When three or five persons walked through the door following each other as closely as comfortable, the system under counted by 40 percent on average.

The results of controlled challenges of PCS2 installed at the entrance door of Room 3 are provided in Table 18. The results are similar to those discussed above, but with better counting accuracy when a single person walked very quickly through the door (no errors) and when three or five person walked through the door at a normal pace following each other as closely as comfortable.

Table 17: Results of Controlled Tests of PCS2 at a Single Interior Door Entrance to Conference Room 1, Numbers are Averages of Three Repeated Challenges

Test Conditions	Room No.	Cor-rect Count	Entrances Through Door		Exits Through Door		Entran-ces or Exits
			Avg. Count	Count - ing Error (%)	Avg. Count	Count -ing Error (%)	Count-ing Error (%)
single person walks through at a normal pace	1	1	1	0%	1	0%	0%
single person walks through at a very fast pace	1	1	0.67	-33%	0.83	-17%	-25%
single person walks through at a normal pace with covered coffee cup	1	1	1	0%	1	0%	0%
single person walks through at a normal pace with open coffee cup	1	1	1	0%	1	0%	0%
single person walks through at a normal pace with a room temperature winter coat with hood on and hands in pockets	1	1	0	-100%	0	-100%	-100%
single person walks through at a normal pace, with a winter coat from the freezer, with hood on and hands in pockets	1	1	0.67	-33%	1	0%	-17%
single person walks through at a normal pace, with a warm laptop computer held flat to the ground	1	1	1	0%	1	0%	0%
two people walk through at a normal pace, side by side, not touching	1	2	1	-50%	1	-50%	-50%
two people walk through at a normal pace, side by side, arm over shoulder	1	2	1	-50%	1	-50%	-50%
two people walk through at a normal pace, second person follows first as close as comfortable	1	2	0.67	-67%	1	-50%	-58%
three people walk through at a normal pace, one after another as close as comfortable	1	3	1.33	-56%	2	-33%	-44%
five people walk through at a normal pace, one after another as close as comfortable	1	5	2.83	-43%	3.5	-30%	-37%

Table 18: Results of Controlled Tests of PCS2 at a Single Interior Door Entrance to Room 3, Numbers are Averages of Three Repeated Challenges

Test Conditions	Conference Room No.*	Correct Count	Entrances Through Door		Exits Through Door		Entrances or Exits
			Avg. Count	Count - ing Error (%)	Avg. Count	Count -ing Error (%)	Counting Error (%)
single person walks through at a normal pace	3	1	1	0%	1	0%	0%
single person walks through at a very fast pace	3	1	1	0%	1	0%	0%
single person walks through at a normal pace with covered coffee cup	3	1	1	0%	1	0%	0%
single person walks through at a normal pace with open coffee cup	3	1	1	0%	1	0%	0%
single person walks through at a normal pace with a room temperature winter coat with hood on and hands in pockets	3	1	0	-100%	0.67	-33%	-67%
single person walks through at a normal pace, with a winter coat from the freezer, with hood on and hands in pockets	3	1	0.67	-33%	1	0%	-16%
single person walks through at a normal pace, with a warm laptop computer held flat to the ground	3	1	1	0%	1	0%	0%
two people walk through at a normal pace, side by side, not touching	3	2	1	-50%	0.67	-67%	-58%
two people walk through at a normal pace, side by side, arm over shoulder	3	2	0.83	-58%	0.83	-58%	-58%
two people walk through at a normal pace, second person follows first as close as comfortable	3	2	1.83	-8%	2	0%	0%
three people walk through at a normal pace, one after another as close as comfortable	3	3	3	0%	3	0%	0%
five people walk through at a normal pace, one after another as close as comfortable	3	5	5	0%	4.67	-6%	-3%

*Room was size of a small meeting room but used for offices

The accuracy of counting of naïve occupant passage through the single door of Conference Room 1 is indicated by the numbers in Table 19. Data are provided for 1.0 hour to 1.5 hour periods on four dates. Excluding data from a period when people were standing in the doorway, the errors in total counts of people entering or exiting the conference room ranged from 0 percent to -14 percent and averaged -5 percent. These errors in total counts reflect some over counting counteracted by some undercounting, thus, the percentage of counting events in which an error occurred was higher (0 percent to 20 percent with an average of 8 percent). On one date, there was a period in which people stood for an extended period in the doorway because the meeting room was full. Total count errors were +29 percent for people entering and -50 percent for people exiting during this period but the number of imperfect accounts was as high as 171 percent of the correct count.

Table 19: Counting Accuracy of PCS2 with Naïve Occupants Passing Through Single-Door Entrances to Conference Room 1 and Room 2

Room	1	1	1	1	1	1	2
Time Period	**9/9**	**9/11**	**10/6**	**10/7 (no standing in door)**	**10/7 (with standing in door)**	**9/9 – 10/7 All Periods (no standing in door)**	**12/18**
Entrances Into Room							
Correct count	20	45	27	62	7	154	31
Counted	17.5	44.5	27	60	9	149	30
Error percent	-13%	-1%	0%	-3%	29%	-3%	-3%
Missed full counts	1	1	0	2	2	4	0
False full counts	0	0	0	0	4	0	0
Undercounts by 0.5	3	0	0	0	3	3	2
Over counts by 0.5	0	1	0	0	3	1	0
Imperfect counts* %	20%	4%	0%	3%	171%	5%	6%
Exits from Room							
Correct count	16	33	29	46	3	124	37
Counted	16	31.5	29	39.5	1.5	116	38
Error %	0%	-5%	0%	-14%	-50%	-6%	3%
Missed full counts	0	2	0	6	1	8	0
False full counts	0	1	0	0	0	1	1
Undercounts by 0.5	1	1	0	1	1	3	2
Over counts by 0.5	1	0	0	0	0	1	1
Imperfect counts* %	12%	12%	0%	15%	67%	10%	14%
Entrances or Exits							
Correct count	36	78	56	108	10	278	68
Counted	33.5	76	56	99.5	10.5	265	68
Error %	-7%	-3%	0%	-8%	5%	-5%	0%
Imperfect counts* %	17%	8%	0%	4%	93%	15%	10%

* Percentage of total events in which a counting error was noted. An event is the passage on one or more persons simultaneously or in close succession through the door, followed by a period with no persons passing through the door.

The accuracy of counting of naïve occupant passage through the single door of Conference Room 2 is indicated by the numbers in right most column of Table 19. On this date, no occupants stood in the door, counting errors were -3 percent and 3 percent for people entering and exiting the room, respectively, and imperfect counts were 10 percent of total counts.

4.4 Discussion

4.4.1 People Counting System Number 1

This PCS1 pilot study indicates that counting accuracy in some situations can be relatively high with errors on the order of 10 percent. Relatively high counting errors occurred in the following demanding situations:

1) people carrying cups of hot coffee;
2) people following very closely behind each other when they pass through the door;
3) people in physical contact when passing through a doorway;
4) people wearing a room temperature winter coat with hood over their head, and
5) direct sunlight heating the floor located beneath the thermal sensors.

The third and fourth of these situations are likely to occur infrequently, at least in most California climates. One could avoid using the PCS1 at locations where direct sun may heat the floor beneath the thermal sensors and the manufacturer indicated that changes in the type of floor mat or moving the detection lines further indoors from the door might have reduced these errors.

In planning the PCS1 testing for office building applications, the required 3.05 m minimum sensor height made the system impractical for many building and conference room entrances. The manufacturer is developing a system that can be installed at a lower height, but this system was not evaluated.

4.4.2 People Counting System Number 2

In the controlled PCS2 challenges, counting accuracy was high when single individuals passed through the doorway at a normal walking pace. Carrying warm objects such as hot coffee or a warm laptop computer did not lead to counting errors. The counter often did not detect a person wearing a room temperature winter coat with hood over their head, but such events are likely very rare for interior doorways. In the first set of controlled tests, there was a substantial undercounting in some highly challenging events such as persons walking through the door at a very fast pace, two people passing through the door simultaneously, and people passing through a door sequentially as closely as comfortable. The accuracy in some of these situations was higher in the second set of controlled challenges. These controlled tests were performed with volunteers as subjects who differed between the two sets of controlled experiments. The results may have differed because the subjects in the first and second set of controlled tests walked at different speeds or with different distances from others. Additionally, as discussed previously, the start threshold was modified between the two sets of controlled tests.

The naïve occupants counting accuracy as they entered or exited Conference Room 1 and Conference Room 2 was generally high, suggesting that the highly challenging events noted above are rare, but more data are necessary before drawing this conclusion. The counter was found to be unsuitable for situations in which people stood in the doorway. In the present studies, this occurred when all seats of the conference room were utilized and a seminar presentation was underway. This situation was not encountered in PCS1 tests.

PCS2 was easy to install and, based on the installation instructions, is usable in most interior doorways. The system does require that the building have a BACnet communication system, which limits its applicability in the current building stock.

4.4.3 General Observations

This pilot testing of people counting systems has several limitations that prevent any firm conclusions about the suitability of these systems for providing a control signal for demand-controlled ventilation. The tests involved only a few sensors, new sensors, a few installation sites, and limited testing periods. Also, with additional experience the positions of the lines that subjects must cross to trigger a count might be adjusted to improve PCS1 accuracy and the aforementioned settings might be changed to improve the accuracy of PCS2 for specific applications. Based on the pilot findings, it is clear that both counting system have limitations and would need to be used only at appropriate sites and where the demanding situations that led to counting errors were rare. In evaluation of the utility of these people counting systems for demand-controlled ventilation one must keep in mind the advantages and disadvantages of people counting that were discussed in the introduction to this report and that that the widely used alternative sensors for demand-controlled ventilation (low cost carbon dioxide sensors) often have large errors.

No costs were available for the prototype PCS2 as this system is not market ready. The cost of people-counting-based demand-controlled ventilation with PCS1, relative to the cost of CO_2-based demand-controlled ventilation, will depend on the application. The price of the counting hardware for a single door entrance was $1,450 while unit costs for single-point CO_2 sensors are typically $300 to $500. The California Title 24 code requires a no less than one CO_2 sensor per 930 m^2 of floor area where demand-controlled ventilation is employed. Thus, CO_2 sensor costs will be substantially lower for most small or moderate-size rooms if the minimum number of CO_2 sensors is installed. For full building applications, the costs for one or more CO_2 sensor per 930 m^2 of floor area could exceed the cost of people counting hardware. Installation costs per sensor should be similar for both types of sensors. People-counting-based demand-controlled ventilation systems require a measurement system for the outdoor air intake rate which can be costly and inaccurate. CO_2-based demand-controlled ventilation is normally utilized without a system for measuring outdoor air intake flow rates, although, because such measurement systems are absent, minimum ventilation rates per unit floor area may often be poorly controlled. The relative costs will also depend on sensor lifetimes, which are currently unknown for both people counters and CO_2 sensors. Finally, the effectiveness of the systems in controlling minimum ventilation rates will have a large impact on their cost effectiveness. Field studies have found that many of the CO_2 sensors used for demand-controlled ventilation have large errors (Fisk et al. 2009). Thus, CO_2-based demand-controlled ventilation is frequently not providing the desired level of control of ventilation rates. This scale and scope of this pilot study was too small for firm conclusions about the energy savings potential of demand-controlled ventilation based on people counting; however, the findings from this pilot study are sufficiently promising to indicate that further investigations of people counting are warranted.

4.5 Conclusions

The two people counting systems had high counting accuracies, with errors typically less than 10 percent, for typical counting events. Counting errors were high in some highly challenging situations, such as people stand in the zone where the counters detect moving people. Both counting systems have limitations and would need to be used only at appropriate sites and where the demanding situations that led to counting errors were rare.

The requirement for a high sensor height substantially limits the applicability of PCS1. The manufacturer reported that they were developing a system that can be installed at a lower height.

The pilot study scale and scope was too small for firm conclusions about the energy savings potential of demand-controlled ventilation based on people counting; however, the findings from this pilot study are sufficiently promising to indicate that further investigations of people counting are warranted.

CHAPTER 5: Recommended Changes to Specifications for Demand-Controlled Ventilation in California's Title 24 Building Energy Efficiency Standards

5.1 Background

The research described in Chapter 2 through Chapter 4 has implications for the specifications pertaining to demand-controlled ventilation in section 121 of the California Title 24 Standard (California Energy Commission 2008). Consequently, this document suggests possible changes in these specifications based on the research findings. The suggested changes in specifications were developed in consultation with staff from the Iowa Energy Center who evaluated the accuracy of new CO_2 sensors in laboratory-based research (National Buildings Controls Information Program 2009). In addition, the California Energy Commission staff and their consultants in the area of demand-controlled ventilation, provided input for the suggested changes in specifications.

5.2 Existing Specifications in Title 24 for Demand-controlled Ventilation

Appendix B reproduces verbatim the existing specifications for demand-controlled ventilation in Title 24 and associated appendices. Key specifications relevant to this document are described in the following list:

1. Demand-controlled ventilation is required for spaces that have an air economizer; a design occupant density, or a maximum occupant load factor for egress purposes greater than or equal to 25 people per 1,000 ft^2 (40 square foot per person); and that are either single zone systems with any controls; or multiple zone systems with direct digital controls to the zone level. There are exceptions to this requirement for certain space types which include classrooms, call centers and medical facilities.

2. For each system with demand-controlled ventilation, CO_2 sensors must be installed in each room with no less than one sensor per 10,000 ft^2 of floor space. CO_2 sensors must be located in the room between 3 ft. and 6 ft. above the floor or at the anticipated height of the occupant's heads.

3. 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 or calibrated at start-up, 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 121(b)2 to the zone serviced by the sensor at all times that the zone is occupied.

4. The CO_2 sensor(s) reading for each zone shall be displayed continuously, and shall be recorded on systems with DDC to the zone level.

The acceptance requirement for demand-controlled ventilation system include a functional test demonstrating that economizer system dampers open and close as intended to high and low CO_2 concentrations

5.3 Key Related Research Results

This section briefly describes the key results of the California Energy Commission and U.S. Department of Energy supported research that serve as the technical underpinning for the subsequent recommended changes in the specifications for demand-controlled ventilation in Title 24. These research findings are described in much greater detail in the following references (Fisk et al. 2009; Fisk et al. 2010; Hong and Fisk 2009) and in Chapters 2-4 of this document. Some of the text below was drawn directly from the cited documents.

5.3.1 CO_2 Measurement Accuracy

Studies of the accuracy of deployed CO_2 sensors used for demand-controlled ventilation in California indicate that a substantial fraction of CO_2 sensors had errors greater than specified in Title 24. Forty seven percent of sensors had errors greater than 75 ppm at a concentration of 760 ppm and 40 percent of sensors had errors greater than 75 ppm at a concentration of 1,010 ppm. A significant fraction of sensors have much larger errors, for example, larger than 300 ppm. These concentrations of 760 and 1,010 ppm are typical of the set point concentrations at which demand-controlled ventilation systems increase outdoor air ventilation rates. Thus, overall many CO_2 sensors do not meet accuracy requirements.

Sensors from some specific manufacturers and with particular design features had a better average accuracy than other sensors. The use of sensors only in these categories, while helpful, would not result in widespread compliance with the Title 24 accuracy requirements.

A significant number of sensors in all age categories had large errors. Thus, replacing sensors every few years also would not solve the accuracy problem.

Because the results obtained from energy management systems generally agreed well with results obtained from the sensor displays, the measurement errors appeared to be primarily a consequence of sensor problems and not due to translating the sensor output signals to building energy management systems.

In analyses of a nine faulty sensor samples, four of the sensors had an output signal that was essentially invariable with CO_2 concentration, yet these sensors were still deployed, indicating that facility managers are not always aware of obviously faulty sensors.

In a laboratory-based accuracy study of 15 new single-location CO_2 sensor models performed by the Iowa Energy Center, many of the new CO_2 sensors had errors greater than 75 ppm, and errors greater than 200 ppm were not unusual. Maximum new sensor errors approached 500 ppm.

Pilot-scale studies of the accuracy of multilocation CO_2 monitoring systems were too limited for firm conclusions about the accuracy of these systems; however, the limited results obtained were encouraging. The study results illustrate the advantage of incorporating a measurement of outdoor air CO_2 concentration with each sensor to offset the indoor air CO_2 concentration measurement errors. Using indoor-outdoor CO_2 concentration differences offset measurement errors. For widespread acceptance, it seems likely that the costs of these systems will need to be reduced.

Together, the findings from the laboratory studies of the Iowa Energy Center and the field studies supported by the California Energy Commission indicate that many CO_2-based demand-controlled ventilation systems will fail to meet the design goals of saving energy while assuring that ventilation rates meet code requirements.

5.3.2 Spatial Variability of CO_2 Concentrations in Occupied Meeting Rooms

Multipoint measurements of CO_2 concentrations in occupied meeting rooms were completed to provide information for locating the CO_2 sensors in meeting rooms. The Title 24 standard requires that CO_2 be measured between 0.9 and 1.8 m above the floor with no less than one sensor per 930 m^2 of floor area. In some of the meeting rooms, concentrations at different wall-mounted sample points varied by more than 200 ppm and concentrations at these locations sometimes fluctuated rapidly. These concentration differences may partly be a consequence of the high CO_2 concentrations in the exhaled breath of nearby occupants. Because the results of the multipoint measurements varied among meeting rooms, this research does not result in definitive guidance for locating sensors in meeting rooms; however, the results suggest that measurements at return-air grilles may be preferred to measurements at wall-mounted locations. In four out of seven data sets, CO_2 concentration at return-grille locations fell between the maximum and minimum of CO_2 concentrations at wall-mounted locations and in five of seven data sets, the period average concentration at return grilles was within 10 percent of the period average concentration measured from sample points on walls.

5.3.3 Performance of Optical People Counters

Pilot-scale studies evaluated the counting accuracy of two people counting systems that could be used in demand-controlled ventilation systems, instead of CO_2 sensors, to provide control signals for modulating outdoor air ventilation rates. The evaluations included controlled challenges of the people counting systems using preplanned movements of occupants through doorways and evaluations of counting accuracies when naïve occupants (for example, occupants unaware of the counting systems) passed through the building or room entrance doors. The two people counting systems had high counting accuracies with errors typically less than 10 percent for typical nondemanding counting events; however, counting errors were high in some highly challenging situations, such as multiple people passing simultaneously through a door. Counting errors, for at least one system, can be very high if people stand in the sensor field of view. Both counting system have limitations and would need to be used only at appropriate sites and where the demanding situations that led to counting errors were rare.

5.3.4 Energy Savings Potential from Demand-Controlled Ventilation in Occupied Meeting Rooms

National level data indicate that average minimum ventilation rates in offices are either 13 or 38 L/s-person. The different average minimum ventilation rates are the result of different measurement protocols but both values are well above the minimum ventilation requirement in California which is approximately 7 L/s-person. These numbers suggest potential energy savings from use of demand-controlled ventilation in general offices to bring the average minimum ventilation rate into alignment with the Title 24 requirement. Modeling and cost analyses, performed to assess this potential, indicated that demand-controlled ventilation would generally not be cost effective for general office spaces in California if existing office buildings have 13 L/s-person of ventilation but would often be cost effective if existing buildings have 38 L/s-person of ventilation.

5.4 Recommendations

Based on the research described above, many existing CO_2-based demand-controlled ventilation systems will fail to meet the design goals of saving energy while assuring that ventilation rates meet code requirements. However, the potential energy savings from properly operating demand-controlled ventilation systems appear to be substantial in magnitude. Thus, it is appropriate to consider how the specifications for demand-controlled ventilation in the Title 24 Standards could be changed to improve the performance of demand-controlled ventilation systems. The following text describes recommended changes in specifications and a discussion of the recommendations. There is some overlap in the language within the various recommendations that should be removed if multiple overlapping recommendations are adopted.

5.4.1 Recommendation 1

5.4.1.1 Description of Recommendation 1

CO_2 sensors installed in new installations of demand-controlled ventilation shall have inlet ports and written protocols that make it possible to calibrate the deployed sensors using CO_2 calibration gas samples. The inlet ports must provide paths for introducing calibration gas samples into the sensors. The protocols must provide the guidance that a facility manager or building control system professional needs to check and, if necessary, adjust the sensors' calibration' using, at a minimum, two calibration gas samples. The calibration protocol shall specify that one calibration gas sample has a CO_2 concentration between 950 ppm and 1,050 ppm, with the actual concentration of the calibration gas known within ± 2 percent. The protocol shall specify calibration with a second calibration gas concentration of either zero ppm CO_2 or between 450 ppm and 550 ppm CO_2, with the actual concentration of the calibration gas known within ± 2 percent.

Exception: The inlet port and calibration protocol are not required if the sensor manufacturer or their agent maintains a sensor exchange program in which deployed sensors are replaced with new or used factory-calibrated sensors at least once per year.

5.4.1.2 Discussion of Recommendation 1

The accuracy of CO_2 sensors used for demand-controlled ventilation must be improved if demand-controlled ventilation systems are to provide the intended energy and indoor environmental quality benefits. Based on the previously-described research (Fisk et al. 2010), restricting the allowable sensor designs will not assure widespread compliance with the Title 24 accuracy requirements. CO_2 measurement accuracy cannot be assured if sensors are not calibrated. Many sensors utilized today cannot practically be calibrated after deployment due to the absence of an inlet port and/or calibration protocol. This recommended change in Title 24 specifications would enable calibrations of all deployed sensors unless the manufacturer maintains a sensor exchange program in which deployed sensors are replaced with new or used factory-calibrated sensors at least once per year. The recommended changes in specifications would also provide incentives to manufacturers to offer sensor exchange programs.

Manufacturers of sensors that already meet these requirements are likely to be supportive of the change in specifications. Many of the existing CO_2 sensors marketed for demand-controlled ventilation do not meet the requirements in this recommendation, thus, substantial industry opposition to the changes should also be expected. Also, it is important to note that making it possible to calibrate deployed sensors does not assure that the calibrations will actually be performed. A significant fraction of CO_2 sensors already meet these requirements; however, in the field studies by the authors no facility manager reported that they had calibrated their CO_2 sensors subsequent to the initial sensor installation period. It is hoped that as the results of research demonstrating large CO_2 measurement errors become known, calibrations will become more common.

No analyses have been performed to determine if sensors meeting the requirements of Recommendation 1 have a significantly higher cost; however, compliant sensors are commonly used today suggesting that incremental costs, if any, are modest. The resulting energy savings will reduce energy costs by an amount that has not been determined.

An alternative or supplement to Recommendation 1 would be to establish an independent sensor validation program that periodically evaluates samples of sensors of various types. A one-time sensor evaluation after a new sensor is introduced into the market may not be adequate. Only sensors on a list of those that pass this program would be compliant with Title 24 requirements. It would be best if the program costs were not paid by sensor manufacturers so that the testing organization is not beholden to the sensor companies. Such a program would be expected to improve at least the initial accuracy of CO_2 sensors used for demand-controlled ventilation, it would not rely on facility managers to implement calibrations, and it would not restrict any sensor design features. A main drawback is the difficulty of establishing and financing of the independent sensor validation program. In addition, because sensor calibrations may change over the life of the sensor, such a sensor validation program would not assure that sensor accuracy is maintained.

5.4.2 Recommendation 2

5.4.2.1 Description of Recommendation 2

Within 60 days after installation in a building, all CO_2 sensors installed for demand-controlled ventilation shall be calibrated, using the manufacturer's recommended protocol, to assure CO_2 measurements are accurate within ± 75 ppm. The protocol must check and, if necessary, adjust the sensor's calibration using, at a minimum, two calibration gas samples, one with a CO_2 concentration between 950ppm and 1050 ppm and the second with a CO_2 concentration of either zero ppm or between 450 ppm and 550 ppm. The concentration of the CO_2 in the calibration gases shall be known within ± 2 percent.

Exception: This calibration is not required if the sensor is provided with documentation demonstrating that a comparable calibration was implemented for the specific sensor within the past 90 days and that the sensor is accurate within ± 75 ppm at 500 ± 50 and 1000 ± 50 ppm CO_2 concentrations when measured at sea level and 77 °F (25°C).

5.4.2.2 Discussion of Recommendation 2

The accuracy of CO_2 sensors used for demand-controlled ventilation must be improved if demand-controlled ventilation systems are to provide the intended energy and indoor environmental quality benefits. Based on the previously-described research (Fisk et al. 2010), restricting the allowable sensor designs will not assure widespread compliance with the Title 24 accuracy requirements. The studies of the accuracy of new CO_2 sensors by the Iowa Energy Center (National Buildings Controls Information Program 2009) demonstrated that existing Title 24 requirements do not assure that a large majority of new CO_2 sensors meet the accuracy requirements of Title 24. This recommended specification, if enforced, would assure that new CO_2 sensors receive a calibration and are accurate within ± 75 ppm when initially installed or shortly thereafter. Because sensor calibrations may change over the life of the sensor, such a sensor validation program would not assure that sensor accuracy is maintained.

The automated background calibration features present in many of the existing CO_2 sensor technologies will adjust sensor calibrations based on the lowest CO_2 concentrations experienced. After initial sensor deployment, the accuracy of CO_2 measurements may improve (or occasionally degrade) over a period of a few weeks. Thus, for sensors with an automated background calibration feature, it may be preferable to perform the on-site calibration after 30 days of deployment. Manufacturer's protocols should specify when on-site calibrations should be performed after initial sensor deployment.

This requirement will increase the cost of installing demand-controlled ventilation systems by an amount that has not been determined. The resulting energy savings will reduce energy costs by an amount that has not been determined.

5.4.3 Recommendation 3

5.4.3.1 Description of Recommendation 3

All CO_2 sensors shall have a continuously-readable visual display of the current CO_2 concentration on the sensor. Manufacturer's may provide a cover that makes the display accessible to facility managers but not to other building occupants.

5.4.3.2 Discussion of Recommendation 3

Displays of the currently measured CO_2 concentrations on the CO_2 sensors may make facility managers more aware of faulty sensors that require calibration or replacement. The research described above has shown that sensors that do not respond to changes in CO_2 concentrations and sensors with very large easily recognizable measurement errors are sometimes deployed in buildings (Fisk et al. 2010). Displays of CO_2 concentration should also make it easier for controls contractors and facility managers to assure that CO_2 concentration at the energy management and control system matches the concentration at the sensor, for example make it easier to detect and avoid signal processing errors. Finally, displays will facilitate the process of calibrating deployed CO_2 sensors.

5.4.4 Recommendation 4

5.4.4.1 Description of Recommendation 4

Change the existing specification in Title 24 that reads as follows "CO_2 sensors shall be located in the room between 3 ft. and 6 ft. (0.9 and 1.8 m) above the floor or at the anticipated height of the occupants heads" to "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 occupant's heads or in the return air duct if the return air duct contains only air from the room for which demand-controlled ventilation is implemented. Sensors shall not be installed in return air ducts if the room has a ventilation system designed to produce a displacement air flow pattern between the floor and the ceiling or if the ceiling is more than 14 ft. (4.3 m) above the floor. Sensors shall not be installed in return-air plenums or at the plane of the return-air grille."

5.4.4.2 Discussion of Recommendation 4

The research summarized above found that CO_2 concentrations at different locations on walls of meeting rooms could differ by more than 200 ppm and fluctuate considerably with time (Fisk et al. 2010). The study was too small for definitive conclusions; however, relative to a CO_2 measurement at a single location on a meeting room wall, a measurement in a return air duct appears to be as representative, and possibly more representative, of the average CO_2 concentration in the room. CO_2 sensors installed on walls may be exposed to air from within wall cavities if the room is slightly depressurized relative to the wall cavity because the electrical wiring for wall-mounted sensors normally extends through an unsealed hole in the wall behind the sensor. Also, wall- mounted sensors may occasionally be exposed to the jets of low-CO_2 supply air as these jets can flow across ceilings and down walls. The existing prohibition against duct-mounted sensors was likely motivated by concerns that low-CO_2 supply air exiting a ceiling mounted supply air diffuser may short circuit to a return grille, causing the return air CO_2 concentration to be substantially lower than the average concentration in the room. While such short circuiting can occur, studies of indoor air flow made using tracer gases in rooms with traditional high velocity air supplies indicate that substantial short circuiting is not common (Fisk and Faulkner 1992). Measurable short circuiting is most likely when the supply air is used for heating (Fisk et al. 1997) and prolonged heating of meeting rooms with a high occupant density, where demand-controlled ventilation is required, may be uncommon. Thus, while there is not enough evidence to justify requiring that CO_2 sensors be installed in return ducts as opposed to on walls, there is also not sufficient justification to prohibit locating CO_2 sensors in return ducts. The prohibition against duct-mounted sensors when the ceiling is more than 4.3 m above the floor is a judgment-based precaution as concentration differences between the occupied zone and the ceiling may be larger when the ceiling height is large. No data were identified confirming that duct-mounted sensors are inappropriate in rooms with high ceilings.

5.4.5 Recommendation 5

5.4.5.1 Description of Recommendation 5

Change the existing specification in Title 24 that reads as follows "For each system with demand control ventilation, CO_2 sensors shall be installed in each room that meets the criteria of Section 121(c)3B with no less than one sensor per 10,000 ft^2 of floor space." to add "In addition to stand-alone sensors that measure the CO_2 concentration at a single location, measurements may be performed with measurement systems that use tubing, valves, and pumps to measure at multiple indoor locations with a single CO_2 sensor if data are available from each location at least once every 10 minutes."

5.4.5.2 Discussion of Recommendation 5

The purpose of this proposed change in Title 24 language it to make prospective users more aware of multilocation CO_2 measurement systems which tend to use higher quality CO_2 sensors and incorporate an outdoor air CO_2 measurement, both of which can improve accuracy of determining the indoor-to-outdoor CO_2 concentration differences. Pilot-scale studies of the multilocation CO_2 measurement systems were too limited for firm conclusions about system accuracy but the findings were encouraging (Fisk et al. 2010).

5.4.6 Recommendation 6

5.4.6.1 Description of Recommendation 6

The required building space types for which demand-controlled ventilation is required in Title 24 should not be expanded to include general office spaces; however, demand-controlled ventilation should continue to be optional for general office spaces.

5.4.6.2 Discussion of Recommendation 6

Model results, summarized above, evaluated the potential energy savings and cost effectiveness of implementing demand-controlled ventilation in general office spaces. Given the model findings and the uncertainty about minimum ventilation rates in the existing office building stock, there is a large uncertainty about the cost effectiveness of demand-controlled ventilation in general office spaces in California climates. Consequently, we do not recommend requiring demand-controlled ventilation in general office spaces.

5.4.7 Recommendation 7

5.4.7.1 Description of Recommendation 7

At this time, Title 24's specifications pertaining to demand-controlled ventilation should not be modified to allow use of optical people counting, in place of CO_2 sensors, to provide the control signal for demand-controlled ventilation.

5.4.7.2 Discussion of Recommendation 7

Pilot-scale studies were completed to evaluate the performance of two optical people counting systems potentially suitable for use in demand-controlled ventilation systems (Fisk and Sullivan 2009). The counting errors were generally small, indicating the long-term potential of applying people counting for demand-controlled ventilation; however, in some highly demanding situations counting errors were large. Further research is needed, and product improvements may be necessary, before one can be confident that optical people counting systems provide a sufficiently accurate count of people to serve as a control signal for demand-controlled ventilation.

5.5 Discussion

Changes in demand-controlled ventilation sensor technologies and practices are necessary if demand-controlled ventilation is to consistently save energy and assure adequate ventilation. Based on the multifaceted research results, this document describes five recommended changes to the specifications in Title 24 for demand-controlled ventilation and makes two recommendations to not change aspects of Title 24. Enacting the suggested recommendations should help demand-controlled ventilation to achieve its potential but they will definitely not eliminate all sensing problems in demand-controlled ventilation systems. Further research to evaluate and develop alternatives to the widely used low-cost single location nondispersive infrared CO_2 sensor may be needed if demand-controlled ventilation is to reach its full potential. Although the recommendations in this report were developed with input from the California Energy Commission and the Iowa Energy Center, a thorough evaluation all of the ramifications of implementing these recommendations was beyond the supporting research project scope. Consequently, the California Energy Commission will need to further evaluate these recommendations.

CHAPTER 6:
Relationship of Classroom Ventilation Rates with Student Absence

6.1 Background

The supply of outdoor air ventilation into a building decreases the indoor air concentrations of pollutants generated indoors; however, increased ventilation increases energy costs. Indoor-generated pollutants include chemical emissions from the building and its physical contents with potential irritant, toxic, allergenic, or odorous properties and also potentially infectious and odorous emissions from people. Historically, ventilation rate (VR) guidelines were based on laboratory studies to control odors from occupants for the satisfaction of visitors (Seppanen et al. 1999). Accumulating evidence, mostly from offices, now suggests that lower VRs in buildings are associated with increases in a variety of adverse health effects, such as infectious respiratory disease, acute symptoms, or impaired cognition or performance (Seppanen et al. 1999). Evidence also shows that a substantial proportion of classrooms do not provide the minimum rates of ventilation specified in standards (Daisey et al. 2003). The scientific evidence on the relationships between VRs and specific human health outcomes is still very limited, especially for schools. School-age children spend 15 percent to 25 percent of their time indoors at school, more than in any other indoor environment except the home (68 percent) (Klepeis et al. 1996). It is important to determine how VRs influence student health, to develop minimum ventilation standards for classrooms that strike a balance between health and the energy costs of providing ventilation

Available limited evidence suggests that lower VRs in offices, schools, and dormitory rooms are associated with increased illness absence (Seppanen et al. 1999; Sun et al. 2011). Only one available study provides information on relationships between VRs in classrooms and the health of students, as indicated by total absence. Shendell et al. (2004) reported that higher classroom ventilation rates were associated with a substantial reduction in student absence. This study used rough measurements for analyses – short, one-time measurements of CO_2 in each classroom as proxies for VRs throughout the school year, and an outcome of total absence, which includes illness absence but also other types of absence unlikely to be influenced by VR.

This paper reports findings of a study, conducted in California elementary schools, on the associations between VRs in classrooms and illness-related school absences, using illness absence as an indicator of health effects sufficiently severe to require staying home from school. Illness absence can be related to respiratory infections, asthma, allergies, gastrointestinal infections, or other disease. The primary hypothesis was that decreased VRs in classrooms would be associated with increased illness absences resulting from increased indoor airborne concentrations of respiratory virus and consequent increased exposure and infection. Such absences might also result to a lesser extent from other airborne agents related to asthma, allergies, or infectious gastrointestinal illness.

6.2 Methods

To provide improved estimates of relationships between classroom VRs and illness absence, information was collected from a large number of schools in three climate zones within California, over two school years, with sufficiently detailed data to estimate daily ventilation rates and daily illness-related absence by classroom. Web-connected CO_2 sensors were installed in classrooms, allowing remote collection of real-time data for estimating daily ventilation rates. Data on student absence and demographic were obtained from the participating school districts.

The associations of VRs with absence were quantified using statistical models that controlled for several potential confounding factors including socio-economic status, grade level, gender mix, and class size. (The energy costs of classroom ventilation and some financial implications to school districts and families from changes in absence rates were also estimated. These will be reported in Chapter 7.)

6.2.1 Sample Design and Selection for Epidemiologic Analysis

The sample design started with aggregation of the 16 Building Climate Zones of the California Energy Commission[6] into a smaller number of climate regions with relatively homogeneous heating and cooling degree-days levels (see Figure 21 for boundaries). Included in the study were three climate regions with large populations: South Coast (SC), with mild winters and warm summers; Bay Area (BA), with mild summers and winters; and Central Valley (CV), with cold winters and hot summers.

Within each selected climate region, the largest school district (by student enrollment) was identified and invited to participate in our study. If they were unable or declined to participate, the next largest school district was contacted, and this process continued until participation by an eligible district was arranged. An eligible school district needed to be willing and able to provide us with the following data:

- classroom-level daily illness-related absence data
- non-identifiable annual student STAR Math and English scores for the students in the monitored classrooms (for the current and prior years).

Within each participating school district, up to 10 elementary schools were selected. To include schools across a range of socioeconomic levels, schools in each district were first ranked by the percent of students who participated in the free or reduced price meals program, used as a surrogate for socioeconomic status[7]. The distribution was divided into five quintiles, and the two largest schools per quintile selected for potential participation.

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[6] http://www.energy.ca.gov/maps/renewable/building_climate_zones.html

[7] http://www.cde.ca.gov/ds/sh/cw/filesafdc.asp, Categorical Allocations & Audit Resolution, School Fiscal Services Division of the California Department of Education, accessed on date Sept 12, 2008

Eligible schools needed to meet the following criteria:

- approval by their Principal to participate;
- approximately six available 3rd, 4th, or 5th grade classrooms, in either permanent or portable buildings, with wired Internet (Ethernet) connections;
- school permission to allow mounting and connection to the Internet of one environmental sensor in each study classroom and one sensor outside at the school, for the duration of the study (two school years);
- agreement by the school or school district to provide student data for study classrooms on both daily classroom-level illness-related absence, and annual individual-level but unidentifiable test scores including linked scores for the current and prior school years.

Within each participating school, approximately six classrooms, two each in 3rd, 4th, and 5th grade, were selected. Eligible *classrooms* needed to meet the following criteria:

- students spending most of the day in the same 3rd, 4th, or 5th grade classroom (rather than moving between multiple classrooms);
- single, not combination, grade classroom;
- providing a general education curriculum, not a dedicated special education classroom.

Some participating classrooms, upon becoming ineligible during the study due to change in use, were replaced by alternate eligible classrooms when feasible; others were simply excluded going forward. Only data from eligible periods in each classroom were included in analyses.

6.2.2 Data Variables for Epidemiologic Analysis

6.2.2.1 Student Data

The primary dependent variable was daily illness absence per classroom, included in analyses as a daily count. Total classroom enrollment data was available from all districts (approximated as the sum of all demographic counts per classroom), on a daily or less frequent basis; if available less than daily, data were backfilled to prior days using available enrollment counts until a prior available periodic count. Other demographic data for students, as classroom-level proportions, were collected as potential covariates: participation in free or reduced price meal program, English-learner status, gifted status, special education status, gender, and race/ethnicity. Participation in free or reduced price meal program was included as an indicator of socioeconomic status, known to be associated with susceptibility to acute lower respiratory tract infections (Graham 1990).

6.2.2.2 Environmental Data

Installed in each participating classroom, and at one outdoor location at each school, were small (2 in x 4 in x 8 in) web/Ethernet-connected sensors (the Nose ™ by PureChoice) that measured carbon dioxide, temperature, and relative humidity in real time. The sensors transmitted the data to the manufacturer, as 5-minute averaged values of CO_2 concentration (in parts per million, ppm), temperature (in degrees Fahrenheit, ºF), and relative humidity (in percent). The nondispersive infrared CO_2 sensors had a resolution of 10 ppm, a rated accuracy of the larger of 5 percent or 100 ppm, and a range of 0-2,000 ppm. A computer server at Lawrence Berkeley

National Laboratory downloaded these data directly from the PureChoice server daily and incorporated them into our database. Some sensors became inoperable for various periods or permanently during the study. When feasible, they were restarted or replaced, but this was not always possible. Missing sensor data were not estimated, so days in a classroom with missing sensor data contributed missing values for ventilation rate averages.

Ventilation rate per person in each classroom each school day (V_o) in L/s per person was estimated in a mass balance model that used the indoor equilibrium concentration minus the corresponding outdoor CO_2 (Equation {6.1}). The daily indoor equilibrium CO_2 concentration for each classroom was calculated as the peak value of a 15-minute moving average of indoor CO_2 values between 7 AM – 3 PM each day. The corresponding outside CO_2 concentration, originally planned as the 60-minute outdoor averaged CO_2 for the period ending at the midpoint of the selected 15-minute indoor period, was instead, due to errors in outdoor sensor readings, estimated in analyses as 400 ppm across all schools.

$$V_o = N/(C_{max15} - C_O) \qquad 6.1$$

where

V_o = outdoor air flow rate per person (L/s person)

N = CO_2 generation rate per person (see Note below)

C_{max15} = maximum 15-minute moving average classroom CO_2 concentration

C_O = outside CO_2 concentration at time of C_{max30} (estimated as 400 ppm)

Note: The occupant CO_2 generation rate (N) is based on a value of 0.0043 L/s for children (Haverinen-Shaughnessy et al. 2011).

The researchers wished to define a lag period for constructing summary VR exposure metrics that would be likely to include relevant periods for the predominant diseases causing illness absence in schools. Available information on time lag after exposure to infectious respiratory disease until disease development, reviewed in determining metrics and models to use in analyses, showed a broad range of lag periods for different infectious agents (one day to three weeks or more), (for example, (Lessler et al. 2009)). Little information was available about the relative contribution of specific disease agents in explaining school illness absence. Therefore, analyses were performed including different averaged periods of VR, all ending on the day before which illness absence was assessed.

Based on the daily VR estimates, multiple aggregate VR metrics were constructed to use in analyses: average daily VRs over the 3-, 7-, 14-, and 21-day periods immediately prior to each day of modeled illness absence. Based on available knowledge, the 7-day period was chosen as the primary metric, including the estimated 95 percent upper confidence limit of the incubation period for multiple respiratory agents (rhinovirus, adenovirus, respiratory syncytial virus, influenza, parainfluenza, and coronavirus) (Lessler et al. 2009). The other metrics were considered exploratory. The 3-day metric included upper 95 percent confidence limits for only rhinovirus, influenza, and parainfluenza (Lessler et al. 2009).

6.2.2.3 Other Covariates

Other data variables available for analyses included the school district (SC, CV, BA); the school, grade level (3, 4, or 5); total classroom enrollment; building type (permanent or portable); type of ventilation (natural, mechanically ventilated without AC, or AC); day of week; and winter season (December through February).

6.2.3 Data Management and Epidemiologic Analysis Methods

A database was created to combine data collected from the environmental sensors and school districts. Extensive data checking and cleaning were performed to insure that: data analyzed was only from eligible periods in each classroom (for example, re eligible grade level and special education status); that measured CO_2 levels were credible; and that reported illness absence data were plausible. Data from any classroom during ineligible periods were excluded. Only full school days were included in VR estimates; the periodically scheduled short (minimum) days at each school, on which peak CO_2 was less likely to estimate a true equilibrium level and thus VR, were excluded, although illness absence on these days was included. Peak indoor CO_2 levels considered implausible for equilibrium levels in occupied classrooms during a school day (below 600 ppm and above 7,000 ppm) were excluded. Because CO_2 sensors outdoors turned out not to be stable with outdoor temperatures, all outdoor measurement data for CO_2 were excluded.

Descriptive data analyses were performed on the distribution of VRs and illness absence rates for all classrooms and selected subgroups. In analytical models at the classroom-day level, the relative change in absence per each change of 1 L/s per person of VR was estimated. A zero-inflated negative binomial (ZINB) models was used, due to extremely skewed data, with many values of 0 for daily illness absence in classrooms. Illness absence count on each classroom day was the outcome, with averaged VR periods as the primary exposure (3 day, 7 day, 14 day, and 21 day exposure periods in separate models). Including illness absence counts per classroom as the outcome with a covariate of total enrollment per classroom was equivalent to analyzing for proportion of illness absence. ZINB models contain two components: zero inflation (ZI) model to estimate whether each observation could ever be nonzero, and a negative binomial (NB) model to estimate the values of the observations with a nonzero probability of being positive. Other covariates in the NB model included day of the week, grade level, class enrollment, proportion in school lunch program, and proportion male, and in the ZI model, day of the week, winter season, and class enrollment. Ventilation type was too closely confounded with school district for inclusion in models. Sixteen models were constructed: each of the four VR metrics used separately for each of three school districts and for all districts combined. Inference for the above models was performed using a bootstrap, by resampling the schools within districts.

Based on the fitted ZINB models, illness absence was predicted at specific VR levels, in each school district and all districts combined. Such predictions are made for specific selected values of each independent variable included in the model. Where possible we chose values representing the mean of a variable in the entire dataset. The models predicted the illness absence at specific VR levels by district, for a 5th grade classroom with 26 children enrolled, of whom 52 percent were male, and 63 percent participated in the free or reduced price meals program, on a Monday in the nonwinter season.

6.2.4 Estimating Potential Benefits of Increased Ventilation Rates

Two kinds of potential benefits associated with reduced illness absence were estimated for specific changes in VRs. It is difficult to estimate from available data all the benefits of reduced illness absences on decreased health care costs. First, financial benefits to school districts of decreased student illness absence were estimated. The State of California funds school districts based not on enrollment but on student attendance, also known as Actual Daily Attendance (ADA), which excludes any absences. Students generate revenue by contributing to the total ADA for a school year, by equation 6.2:

$$\Sigma R_i = \Sigma\,(ADA_i * R_L) \qquad 6.2$$

where

R_i = revenue generated for district by student (i) during a school year
i ranges from 1 to the total number of students attending school in a district
ADA_i = actual daily attendance for student (i) = total days attended by student (i) in the school year divided by the 180 days of school taught
R_L = revenue limit per ADA ($5,300 per pupil for unified school districts in 2009-10 (although varies by grade level and learning track)

The benefits to families resulting from decreased illness absence due to decreased costs from time taken off work or other tasks to care for their children were also estimated. These estimates used a previously reported approach based on employment and earnings data in the National Health Interview Survey (NHIS), an annual, nationally representative survey of U.S. households (Levy et al. 2011), using established cost-of-illness methods and NHIS data on children 6 years to 11 years old attending school, estimated the value of a day for caregiver's time for each child missing school. For employed caregivers, Levy et al. used self-reported daily earnings, or if unemployed, used the value of time for lost household production, according to the cost of hiring someone else to complete the household tasks. Estimates involved a number of conservative assumptions (Levy et al. 2011). The present analysis follows Levy in estimating that 69 percent of the caregivers were employed, with mean annual and daily earnings of $20,087 and $80; value of household production among unemployed caregivers was estimated at $51 daily. The overall averaged value of household production among families with employed or unemployed caregivers was 55.2+15.8 = $71 per day of child illness absence.

6.3 Results

Three school districts in California participated: one each in the SC, BA, and CV regions (Figure 21). The researchers selected a subsample of 10 schools in the SC district and nine in the BA, but included all nine available elementary schools in the CV district. Within each school, the goal was to include 2 classrooms at each of the 3rd, 4th, and 5th grade levels, but the available classroom mix varied slightly from this in some schools. By the end of the study, valid data were collected in 28 schools, from 166 classrooms. Table 20 shows the types of buildings and types of ventilation in the studied classrooms for each school district. The classrooms included 107 in permanent buildings and 55 in portables; and 61 with natural ventilation only, 30 with mechanical ventilation without air conditioning (AC), and 30 with AC. While the BA district classrooms included a mixture of naturally ventilated, mechanically ventilated without AC, and AC, the SC classrooms included no AC, and the CV schools all had AC.

Table 21 provides data on the distributions of estimated equilibrium indoor CO_2 concentrations and estimated VRs in the study classrooms. Ventilation rates differed substantially across districts, with median VRs in the SC, BA, and CV districts of 7.0 L/s, 5.1 L/s, and 2.6 L/s per person, respectively. VRs varied most in the SC district, less in the BA, and relatively little in the CV, with ranges between the 5^{th} and 95^{th} percentiles for VR of 18.0 L/s, 12.2 L/s, and 5.1 L/s per person respectively. VRs also varied by building type, with medians in permanent and portable classrooms of 6.8 L/s and 5.0 L/s per person respectively, and by ventilation type, with medians for natural, mechanical/no AC, and AC of 6.0 L/s, 7.6 L/s, and 2.8 L/s per person respectively.

Table 22 provides descriptive data on the classrooms with valid data available for analyses. All enrolled schools were included except for four in Oakland. Average total enrollment across all studied classroom during the study was 2,358. Average student enrollment in each studied classroom was slightly lower in the BA district (25.9) than in the SC (27.3) or CV (26.3), with third grade enrollment, per classroom and overall in the study, smaller than the higher grades in all three districts. Slightly more males were included in each district. Almost three quarters of the students participated in the National School Lunch Program (official name of the federal Free or Reduced Price Meal Program) in BA and CV, compared to about half in SC. Proportions of racial/ethnic categories varied across the districts: Asian/Pacific Islander, 7 percent to 33 percent; White, 14 percent to 38 percent; Black, 3 percent to 29 percent, and Latino, 20 percent to 51 percent.

Analyses potentially included almost 35,000 classroom days (Table 22). Mean daily classroom proportions of illness absence ranged across districts from 2.11 percent to 2.53 percent, and across grades 3 to 5, were 2.54 percent, 2.25 percent, and 2.30 percent, respectively. Mean proportion of illness absence was higher in the winter months (December-February) within each district and overall. Median proportion of daily classroom illness absence in all categories (not shown) was 0.

Figure 21: Climate Regions Included

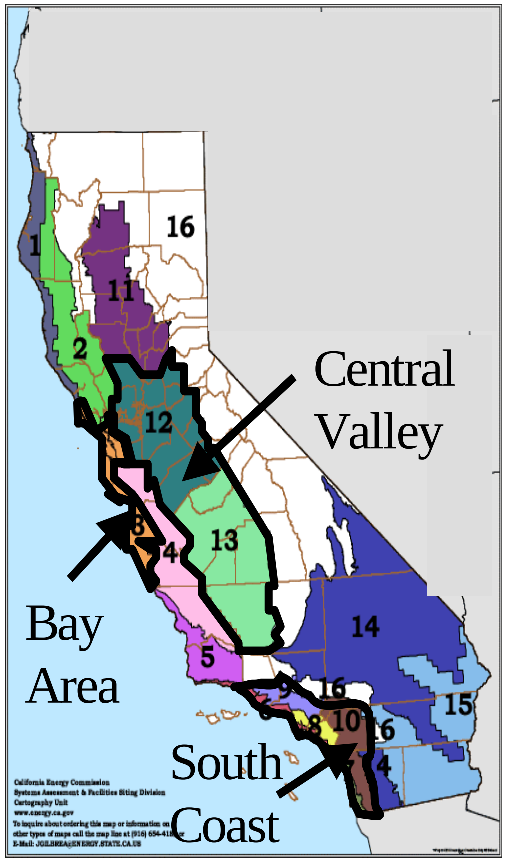


Table 20: Descriptive Information on Selected Study Variables

	District			
	SC	BA	CV	All
Summer temperature	warm	mild	hot	---
Winter temperature	mild	mild	cold	---
Number of schools	10	9	9	28
Number of classrooms	59	52	51	162
Building type for classrooms				
Proportion (number) in permanent buildings	59% (35)	81% (42)	59% (30)	66% (107)
Proportion (number) in portable buildings	41% (24)	19% (10)	41% (21)	34% (55)
Ventilation type for classrooms				
Proportion (number) with natural ventilation	76 % (45)	31% (16)	0% (0)	37% (61)
Proportion (number) with mechanical ventilation, no AC	24% (14)	31% (16)	0% (0)	19% (30)
Proportion (number) with AC	0% (0)	38% (20)	100% (51)	44% (71)
Number of classroom days with ventilation rate data**	11,069	9,615	8,135	28,819
Approximate total enrollment in all 3rd, 4th, and 5th grade classrooms in studied school districts***				
Third grade	10,000	4,000	1,000	15, 000
Fourth grade	10,000	4,000	1,000	15, 000
Fifth grade	10,000	4,000	1,000	15, 000

Abbreviations: AC, air-conditioning; BA, Bay Area; CV, Central Valley; SC, South Coast; VR, ventilation rate

** includes all those with valid VR data, although may not all be included in models; for example, it includes all 28 schools and classrooms, even though some entire schools in BA were excluded from analyses.

*** for example, whether studied or not; numbers rounded to nearest 1,000 to maintain anonymity of participating school districts; data source = http://www.ed-data.k12.ca.us/App_Resx/EdDataClassic/fsTwoPanel.aspx?#!bottom=/_layouts/EdDataClassic/profile.asp?Tab=0&level=06&reportnumber=16&county=50&district=75739 , accessed Apr 3, 2012

Table 21: Distribution of Estimated Equilibrium Indoor CO_2 Concentrations* and Estimated Ventilation Rates by District, Building Type, and Ventilation Type

	Estimated equilibrium CO_2 concentration (ppm)**							VR (L/ sec-person)**						
	Percentiles					Mean	SD	Percentiles					Mean	SD
	5th	25th	50th	75th	95th			5th	25th	50th	75th	95th		
School District														
SC	654	853	1,137	1,699	2,636	1,347	652	2.31	3.98	7.01	11.41	20.33	8.43	5.53
BA	769	1,040	1,405	2,041	3,222	1,632	770	1.83	3.15	5.14	8.08	13.99	6.17	4.03
CV	1,204	1,854	2,377	3,028	4,168	2,492	901	1.37	1.97	2.61	3.55	6.43	3.11	2.01
Building Type														
Permanent	702	984	1,386	1,997	3,021	1,568	734	1.97	3.23	5.24	8.84	17.11	6.77	4.80
Portable	750	1,257	2,057	2,877	4,082	2,164	1,063	1.40	2.09	3.12	6.03	14.77	4.98	4.53
Ventilation type														
Natural	695	914	1,268	1,813	2,755	1,446	672	2.19	3.66	5.95	10.06	17.49	7.42	4.91
Mechanical / no AC	650	848	1,084	1,424	2,227	1,204	485	2.83	5.05	7.56	11.53	20.63	8.98	5.31
AC	1,008	1,696	2,278	2,950	3,994	2,366	916	1.44	2.03	2.75	3.99	8.50	3.51	2.50

Abbreviations: AC, air-conditioning; BA, Bay Area; CV, Central Valley; SC, South Coast; SD, standard deviation; VR, ventilation rate

* Data in this table include all valid CO2 measurements, without exclusion due to invalid associated illness absence data.

**Because peak indoor CO2 concentrations below 600 ppm and above 7,000 ppm were excluded, these constituted the potential minimum and maximum values across all districts for estimated equilibrium CO2 concentrations, and the corresponding values for minimum and maximum VRs (0.8 and 25.9 L/s per person).

Table 22: Demographic and Illness Absence Data

	District			All
	SC	BA	CV	
Number of Schools	10	5	9	24
Number of Classrooms	59	26	51	136
Building type for classrooms				
Proportion (number) in permanent buildings	0.59 (35)	0.88 (23)	0.59 (30)	0.65 (88)
Proportion (number) in portable buildings	0.41 (24)	0.12 (3)	0.41 (21)	0.35 (48)
Ventilation type for classrooms				
Proportion (number) with natural ventilation	0.76 (45)	0.12 (3)	0	0.35 (48)
Proportion (number) with mechanical ventilation, no AC	0.24 (14)	0.38 (10)	0	0.18 (24)
Proportion (number) with AC	0	0.50 (13)	1.0 (51)	0.47 (64)
Average enrollment per classroom (SD)	27.3 (5.6)	25.9 (5.0)	26.3 (4.8)	26.7 (5.3)
Third grade	23	21	21	22
Fourth grade	29	28	29	29
Fifth grade	29	28	30	29
Average combined enrollment of included classrooms	1,401	561	1,089	2,358
Third grade	345	133	301	598
Fourth grade	541	216	393	892
Fifth grade	515	211	394	867
Average proportion male	0.52	0.52	0.52	0.52
Average proportion National School Lunch Program**	0.49	0.76	0.71	0.62
Average proportion Asian or Pacific Islander	0.28	0.33	0.07	0.22

Average proportion White	0.17	0.14	0.38	0.23
Average proportion Black	0.18	0.29	0.03	0.16
Average proportion Latino	0.38	0.20	0.51	0.38
Number of classroom days with illness absence data*	16,807	7,338	10,562	34,707
Mean daily classroom proportion (%) of illness absence (SD)	2.36 (3.2)	2.11 (3.4)	2.53 (3.3)	2.36 (3.3)
3rd grade	2.42	2.48	2.74	2.54
4th grade	2.38	1.61	2.53	2.25
5th grade	2.29	2.32	2.32	2.30
Winter season***	2.84	2.32	2.95	2.75
Non-winter season	2.19	2.02	2.40	2.22

Abbreviations: SD, standard deviation

* based on all valid IA data eligible for inclusion in models; however, some classroom-days included in these data were not included in models if lacking necessary VR data

** official name of the national Free or Reduced Price Lunch Program

*** Winter is defined as the months of December, January, and February.

Table 23: Unadjusted IRR Estimates* and 95 Percent Confidence Intervals (CI) From Zero-Inflated Negative Binomial Models for Association Between Classroom Ventilation Rate (VR) Metrics and Daily Classroom Proportion of Illness Absence, Per Increase of 1 L/S Per Person VR in Observed Range of 1-20 L/S Per Person**

	School District									All		
	South Coast			Bay Area			Central Valley					
VR averaging period	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value
3 days**	13,363	0.988	(0.980-0.997) p=0.009	5,252	0.979	0.907-1.06 p=0.59	9,781	0.998	(0.979-1.02) p=0.81	28,396	0.988	(0.978-0.997) p=0.011
7 days**	14,318	0.986	(0.975-0.996) p=0.008	5,742	0.974	0.889-1.07 p=0.58	10,120	0.987	(0.965-1.01) p=0.26	30,180	0.985	(0.974-0.996) p=0.007
14 days**	14,559	0.984	(0.973-0.996) p=.008	5,955	0.978	0.876-1.09 p=0.70	10,378	0.989	(0.962-1.02) p=0.43	30,892	0.985	(0.973-0.996) p=0.009
21 days**	14,664	0.984	(0.973-0.996) p=0.008	6,106	0.978	0.866-1.10 p=0.72	10,438	0.980	(0.954-1.01) p=0.14	31,208	0.984	(0.972-0.996) p=0.008

Abbreviations: IRR, incidence rate ratio; L, liter; s, second, VR, ventilation rate;

* estimates are the relative (multiplicative) change in the outcome for each increase of one L/s per person

** bootstrapped

** ending on day prior to day on which illness absence assessed

6.3.1 Modeling Results

Table 23 provides unadjusted estimates (with no covariates in the ZI or NB components of models) and 95 percent CIs from the ZINB models, for the association between classroom VR metrics and daily classroom proportion of illness absence, from the specific district models and the combined district models. Table 24 provides the adjusted estimates, which were very similar to the unadjusted estimates. The model assumes a non-linear relationship in which the relative change per VR unit stays constant, but the absolute change decreases as VR increases. The interpretation of the adjusted estimates for VR in the ZINB model (estimates are of incident rate ratios is: if a classroom were to increase its VR by 1 L/s per person while holding all other variables in the model constant, the expected proportion of illness absence (equivalent to the count, when holding class size constant) would be multiplied by a factor equal to the coefficient. Estimates less than 1.0 indicate decreased illness absence. Changes in illness absence corresponding to multiple unit increases of VR are estimated by exponentiating the estimates accordingly.

For each additional 1 L/s per person of VR, illness absence is estimated to be lower (Figure 22): for the SC, BA, and CV districts, by 1.0 percent to 1.3 percent, 1.2 percent to 1.5 percent, and 0.0 percent to 2.0 percent, respectively, and in the model for all districts combined, by 1.4 percent to 1.8 percent. Only estimates in the SC and combined district models had 95 percent CIs excluding the null. Numbers (n) of eligible classroom-day observations in models were approximately 56 percent and 37 percent lower, for BA and CV respectively, than for SC.

Comparing estimates for the 7-day averaged VR metrics across the separate district models: for each additional 1L/ sec-person of VR, illness absence was estimated to decrease, for the 3-day, 7-day, 14-day, and 21-day periods, by 0.0 percent to 1.2 percent, 1.0 percent to 1.5 percent, 0.9 percent to 1.3 percent, and 1.3 percent to 2.0 percent, respectively. There is a general tendency for these estimates to increase as the averaging period for VR increases, rather than peaking for the 7 day metric as hypothesized. Note that the three districts included were not selected to be representative of California districts, and results from the combined districts model may not be applicable to California school districts generally. There also may be unrecognized confounding in the combined models.

For another set of covariates in the model, days of the week, the most illness absences in each district were reported on Mondays, followed by Fridays or Tuesdays, with the least on Thursdays or Wednesdays. Illness absences by grade varied across districts: in BA, they were highest in third grade, substantially lower in fifth grade, and lowest in fourth grade, but in SC and CV, they were slightly higher in 4^{th} and 5^{th} grades. Male gender was associated consistently with increased illness absence. Proportion of free or reduced price meals was not associated consistently across districts with illness absence, but in the combined model was associated with decreased illness absence.

Figure 23 plots predicted counts of illness absence in the three districts and in the combined data, over the observed range of VRs, based on adjusted models using 7 day averaged ventilation rates and the baseline values of covariates specified in the footnote. The vertical bars at the base of each plot show the VR values of data points on which that the plot was based.

Table 25 provides example predicted data points for VR levels in L/s per person of 1, 5, 10, 15, and 20, and also 4.0 (the estimated mean VR for California K-12 classrooms – see Chapter 7), 7.1 (the minimum VR for classrooms specified in California Title 24), 6.7 and 7.4 (the minimum VRs for classrooms of grade 4-5 and 3, respectively, specified by the current ASHRAE standards (ASHRAE 2010)), and 9.4 (the minimum VR specified for offices in ASHRAE Standard 62-89 in 1989). Increasing VRs from the current mean level of 4 L/s per person to the current minimum required in California of 7.1 L/s per person would result in predicted absolute reductions in IA of 0.1 percent tp\o 0.2 percent and predicted relative reductions of 3.4 percent to 4.8 percent (based on estimates from the 3 school districts studied). Further increasing VRs to 9.4 L/s per person would predict further absolute reductions of 0.1 percent to 0.2 percent and relative reductions ranging from 3.6 percent to 5.0 percent. Increasing VRs from current average levels to 9.4 L/s per person would lead to an approximate 7 percent to 10 percent predicted reduction in illness absences. Increasing average VRs from 4 L/s to 20 L/s per person would reduce illness absence by an estimated 20.7 percent.

Table 24: Adjusted IRR Estimates* and 95 Percent Confidence Intervals (CI) From Zero-Inflated Negative Binomial Models for Association Between Classroom Ventilation Rate (VR) Metrics and Daily Classroom Proportion of Illness Absence, Per Increase of 1 L/S Per Person VR in Observed Range of 1-20 L/S Per Person**

	School District									All		
	South Coast			Bay Area			Central Valley					
VR averaging period	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value
3 days**	13,363	0.990	(0.982-0.998) p=0.01	5,252	0.988	0.963-1.01 p=0.38	9,781	1.000	(0.980-1.02) p=1.0	28,396	0.986	(0.975-0.997) p=0.01
7 days**	14,318	0.988	(0.980-0.997) p=0.01	5,742	0.985	0.951-1.02 p=0.40	10,120	0.990	(0.964-1.02) p=0.47	30,180	0.984	(0.971-0.996) p=0.01
14 days**	14,559	0.987	(0.978-0.997) p=.008	5,955	0.988	0.945-1.03 p=0.61	10,378	0.991	(0.962-1.02) p=0.54	30,892	0.983	(0.969-0.997)\ p=0.02
21 days**	14,664	0.987	(0.977-0.997) p=0.01	6,106	0.987	0.940-1.04 p=0.60	10,438	0.980	(0.952-1.01) p=0.19	31,208	0.982	(0.968-0.997) p=0.02

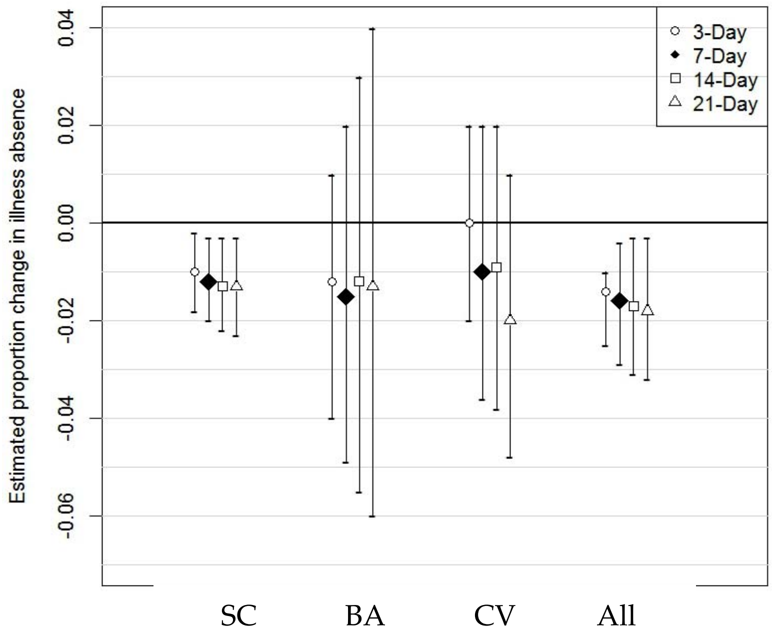
Abbreviations: IRR, incidence rate ratio; L, liter; s, second, VR, ventilation rate;

* estimates are the relative (multiplicative) change in the outcome for each increase of one L/s per person; models adjusted, in the main part of the model, for grade level, day of the week, proportion free lunch program, and proportion male; and in the zero-inflated part, for day of week, winter season, and total count (from demographics data).

** bootstrapped

** ending on day prior to day on which illness absence assessed

Figure 22: Estimated Proportional Change in Illness Absence With Increase of 1 L/S Per Person of VR Within the Observed Range of 1-20 L/S Per Person, Using Four Ventilation Metrics with Different Averaging Periods*



* ventilation averaging metrics end on day prior to day on which illness absence assessed

Figure 23: Predicted Relationship between Ventilation Rate and Proportion Illness Absence in Three California School Districts

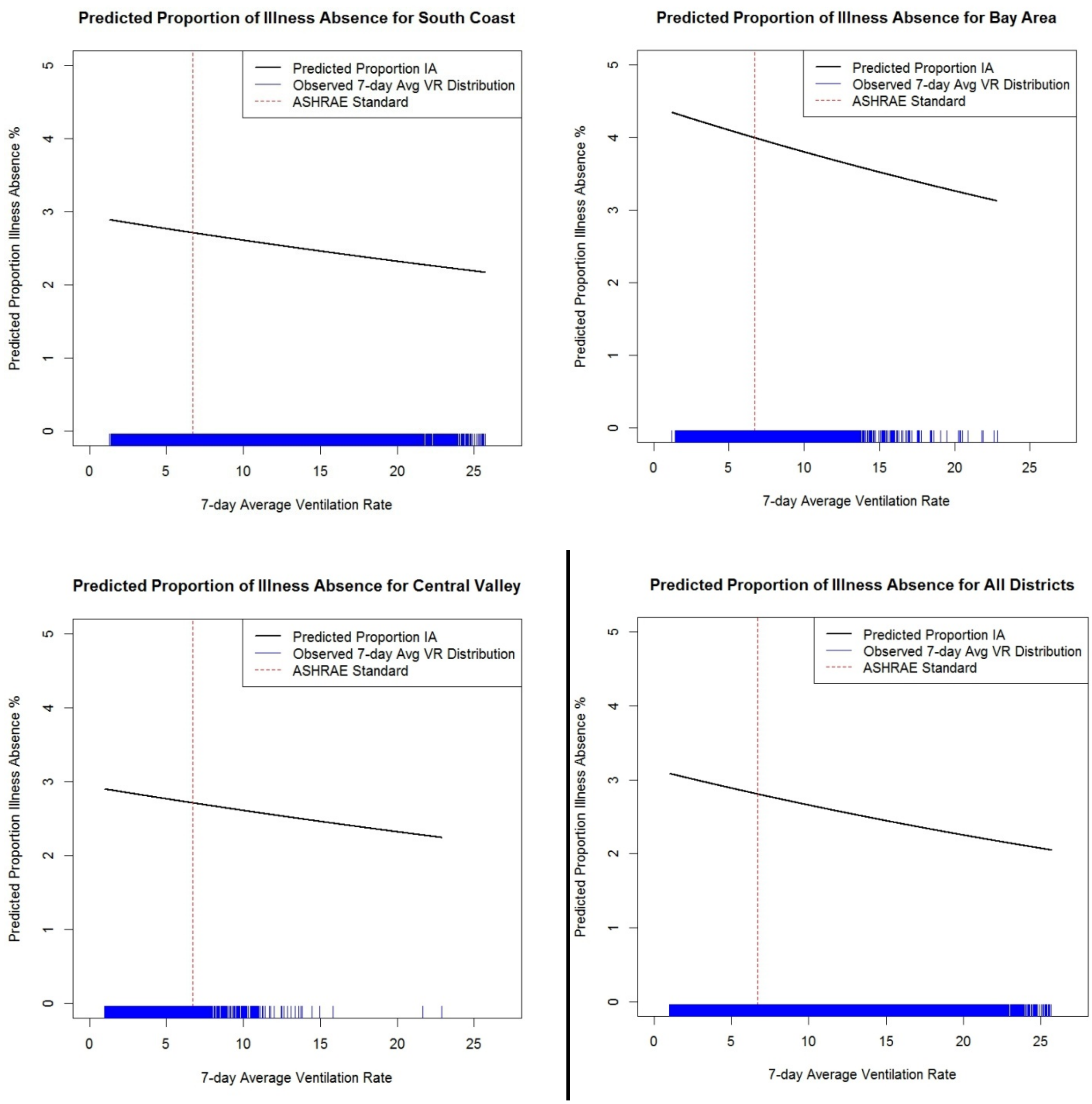


Table 25: Predicted Proportion of Illness Absence at Specified Outdoor Air Ventilation Rates Based on Adjusted Models* Using 7-Day Averaged Ventilation Rates, in 3 California Climate Zones

		Predicted proportion of illness absence			
VR (L/s per person)	VR (cfm per person)	District			All
		SC	BA	CV	
1.0	2.1	0.029	0.043	0.029	0.031
4.0**	8.5	0.028	0.042	0.028	0.029
5.0	10.6	0.028	0.041	0.027	0.029
6.7[1]	14.2 (13[2])	0.027	0.040	0.027	0.028
7.1***	15	0.027	0.040	0.027	0.028
7.4[3]	15.7 (15[4])	0.027	0.040	0.027	0.027
9.4[5]	20	0.026	0.038	0.026	0.027
10.0	21.2	0.026	0.038	0.026	0.027
15.0	31.8	0.025	0.035	0.025	0.024
20.0	42.4	0.023	0.033	0.024	0.023

* assuming specific mix of personal and building covariates:26 children enrolled in each classroom who were in 5th grade, 52 percent male, 63 percent participating in the free or reduced price meals program, on a Monday in the non-winter season.

* estimated mean VR for California K-12 classrooms

1 ASHRAE default standard for classrooms ages 9+ (includes grade 4-5); assumes occupancy of 35 persons/100 m^2

2 ASHRAE default standard for classrooms ages 9+ (includes grade 4-5); assumes occupancy of 35 persons/100 m^2; nominal value, vs. as-calculated value of 13.4 based on this occupant density; exact conversion of standard in SI units is 14.2, because 100 m^2 = 1,076 ft2

*** minimum VR for classrooms specified in California Title 24

3 ASHRAE default standard for classrooms ages 5-8 (includes grade 3); assumes occupancy of 25 persons/100 m^2

4 ASHRAE default standard for classrooms ages 5-8 (includes grade 3); assumes occupancy of 25 persons/100 m^2; nominal value, vs. as calculated value of 14.8 based on this occupant density; exact conversion of standard in SI units is 15.7

5 The minimum VR specified for offices in ASHRAE 62-89 in 1989.

6.3.2 Estimated Benefits from Increased VRs

Potential benefits of reduced illness absence from school include, for the school district, increased revenue from the State for student attendance, and possibly decreased illness absence among teachers and staff. Potential benefits for the children and their families include: reduction in suffering and discomfort from illness, risk of subsequent serious or chronic illness, health care costs, and time and costs of caregiving for children at home. While any of these benefits may be substantial, some are difficult to estimate. The benefits from decreased illness absence, to school districts, of increased revenue from the State for student attendance were estimated. Also estimated were the benefits from decreased illness absence, to families, of decreased costs from lost caregiver wages/time.

Estimated losses in revenue to a California school district from the 2.9 percent illness absence (5.22 annual absence days per student) predicted from the combined districts model at the current average classroom VR (4 L/s per person), is $153.70 per student or $153,700 per 1,000 students. Predicted increase in ADA revenue with specific increases in average classroom VRs are shown in Table 26. With mean VR increased from 4.0 to 7.1 or 9.4 L/s per person, the predicted increases in revenue are $5,300 and $10,600, respectively, per 1,000 students. Benefits to families for decreased costs from lost caregiver wages/time, for these two levels of VR increase, amount to approximately $12,800 and $25,600 per 1,000 students, respectively.

Table 26: Estimated Losses in Revenue to School Districts (Equation 2)

Ventilation rate	Estimated decrease in illness absence proportion (%)	Average decrease in annual illness days per student	Predicted increase in ADA revenue per student	Predicted increase in ADA revenue per student
4.0 to 7.1 L/s per person	0.1%	0.18	$5.30	$5,300
4.0 to 9.4 L/s per person	0.2%	0.36	$10.60	$10,600

Abbreviations: ADA, Actual Daily Attendance

* based on estimates from combined student model with 7-day averaged VR metric, a 180-day school year, and $5,300/year in ADA reimbursement per child

If the relationships estimated in this study were applied to K-12 classrooms throughout California, then for the approximately 6,224,000 students (in 303,400 classrooms in 9,900 schools in 2009-10)[8], an increase in mean VRs from 4 L/s to 7.1 L/s per person would increase annual state funding to school districts by $33M. Among this population, an increase in VR from 4 L/s to 7.1 L/s per person would also produce benefits for families, from decreased costs for caregiver time, amounting to $80M. Valuations of caregiver time include substantial subjectivity and uncertainty. Total estimated benefits equal $113M. A further increase from 7.1 L/s to 9.4 L/s per person would increase annual state funding to school districts by an additional $33M, and increase benefits to families by an additional $80M, for an additional total benefit of $113M. We have not estimated reduced reductions in costs of medical care for students, monetized

[8] http://www.cde.ca.gov/ls/fa/sf/facts.asp

improvements in quality of life for children and families, or any parallel costs related to sick leave for teachers and staff,.

6.4 Discussion

The findings here, although requiring replication, suggest that keeping VRs below recommended levels in classrooms saves energy and money, but may have overriding unrecognized costs of increased health problems and illness absence among students. The findings also suggest that increasing VRs above the recommended minimum levels may further substantially decrease illness absence, within the range of the data analyzed; that is, up to the 95th percentile VR value of about 20 L/s per person, or possibly even the maximum value of 26 L/s per person. All three school districts, in the studied classrooms, had median daily VRs below the Title 24 minimum VR standard of 7.1 L/s per person for classrooms. Thus, over half of the classrooms studied, and in the CV district over 95 percent of classrooms, were supplied with outdoor air at below the mandated rates. Together, these findings suggest a potentially large opportunity to improve the health and attendance of elementary school students in California through provision of increased outdoor air ventilation in classrooms.

Although 95 percent CIs for the estimates for VRs and illness absence excluded the null only in the SC model and the combined-district model, estimates in all districts showed consistent patterns across all models. The lack of statistical significance for estimates from the BA and CV districts, despite point estimates mostly similar to those in SC, may be explained by the substantially lower number of eligible days of classroom data for BA and CV than for SC, leading to wider CIs. This difference in CIs was due to ineligibility in these districts of a number of schools for extended periods. The smaller range of VRs in the CV district may also have made it more difficult to detect a significant association.

The analyses presented here focus on the hypothesis that VR rates in classrooms influence exposures to airborne infectious respiratory agents and consequent illness absence among students. The stronger association with illness absence, however, of longer VR averaging periods seems more consistent with a link between long-term VRs and illness absence, such as might be due to airborne exposures with chronic health effects. Airborne contaminants produced in classrooms include, in addition to potentially infectious agents emitted from occupants, chemical emissions with potential irritant, toxic, or allergenic properties from the building materials and building contents such as furniture, electronic equipment, art supplies, and cleaning and maintenance products. Long-term increase of such exposures might also somehow increase susceptibility to respiratory infections.

Estimated relationships were fairly similar across districts, despite differences between the districts in both climate and types of ventilation. The SC district, with very mild winters and no AC, had the broadest range of VRs and the highest overall VRs. The BA classrooms, also with fairly mild winters, had some naturally or mechanically ventilated classrooms without AC, and some AC classrooms, and intermediate VR levels. The CV district, with hot summers and cold winters and all AC classrooms, had the lowest overall VR levels and the least variation in VRs (windows would likely have been closed during the extended periods with either cooling or heating).

6.4.1 Prior Findings

6.4.1.1 Ventilation Rates and Health

A number of prior studies have reported associations between lower building VRs (or higher CO_2 concentrations used as a surrogate for VRs) and increased health-related outcomes, including building-related symptoms in offices (Erdmann and Apte 2004; Seppanen et al. 1999; Wargocki et al. 2002); febrile respiratory illness in barracks (Brundage et al. 1988); respiratory infections in dormitories (Sun et al. 2011); and respiratory symptoms and nasal patency in school classrooms (Simoni et al. 2011). Other studies have found associations between lower VRs and increased absence metrics in offices, used as indicators of health outcomes. Findings from Milton et al. (2000) show a 2.9 percent decrease in short-term illness absence per 1 L/s per person increase in VR. In contrast, Myatt (2002), found no association between two very high levels of VR, between 40 L/s to 45 L/s per person, and illness absence.

Few of these studies have been conducted in schools. Because classrooms differ from offices and other buildings in the types of indoor pollutant sources, occupant density, and average occupant age (including possible differences in age-related occupant emission and response to infectious agents), the VR and human health relationships may differ between schools and other buildings. Only one available study has investigated relationships between VRs in classrooms and the health of students, as indicated by absence. Shendell et al. (2004) studied annual average classroom absence rates from 434 traditional and portable classrooms in 22 schools in the states of Washington and Idaho. Measurements of the two primary variables analyzed were relatively crude: one-time spot measurements of CO_2 for at most 5 minutes within and outside each classroom to calculate the indoor minus outdoor CO_2 concentrations (ΔCO_2) as an indicator for classroom VRs throughout a full school year, and annual average rates of total classroom absence, which included illness absence but also other types of absence unlikely to be influenced by VR.

Shendell et al. (2004) reported that higher classroom VRs were associated with a substantial reduction in student absence: a decrease of 1,000 ppm in ΔCO_2 within the observed range of 10 ppm to 4,200 ppm was associated with a 10 percent to 20 percent relative decrease (0.5-0.9 percent absolute decrease) in total student absence (which averaged 5.0 percent). These findings, when converted to a comparable metric, can be compared to the findings of this California study. Appendix D presents the calculations and sources supporting this conversion. Assuming that in the Shendell et al. study (2004), all VR-related decreases in the 5 percent total absence rate occurred among illness absences, and that mean illness absences were 2.35 percent as in the present study, then each additional 1 L/s per person was associated with a 2 to 8 percent relative decrease in illness absence, approximately 2 to 5 times larger than the current findings of a 1.2 percent to 1.5 percent relative decrease with this VR change.

In theory, VR is correlated with equilibrium ΔCO_2 concentrations, and would only correlate with random ΔCO_2 values to the extent that these happened to correlate with equilibrium CO_2 concentrations. The equilibrium CO_2 concentration is reached in an indoor space only after a sufficient period of constant occupancy and ventilation. Using ΔCO_2 measurements for classrooms made at random times as proxies for the equilibrium values for CO_2 will result in some underestimation of equilibrium ΔCO_2 and thus overestimation of VRs in the study. This ΔCO_2 measurement method will cause nondifferential misclassification of the VRs, likely to cause underestimation of any true relationships of health effects with VR. In addition, Shendell et al. used the outcome of total absence, much of which would not be expected to vary with VR. Because Shendell et al. (2004) detected such a strong relationship despite the very inexact estimates of VR, the current study using the same underlying relationships and more accurate measurement strategies should detect stronger relationships between VRs and illness-related absences. Yet the current study found a much smaller expected change in illness absence.

6.4.1.2 Ventilation Rates and Respiratory Infections and Illness Absence

Theory and some empirical evidence (Li et al. 2007; Milton et al. 2000; Riley et al. 1978; Riley 1982; Rudnick and Milton 2003; Sun et al. 2011) suggest that lower VRs in buildings could increase airborne transmission of infectious respiratory disease between occupants. Rudnick (2003) concludes from statistical modeling that increased outdoor air supply can prevent the airborne transmission indoors of some common respiratory infections and influenza, but will have little impact on highly contagious airborne diseases such as measles. VR is not expected to influence transmission of disease agents by direct or indirect contact or by short range large aerosols such as from nearby sneezing (unless VR affects susceptibility to infection by influencing unknown indoor exposures acting through unknown mechanisms).

Recorded illness absence (sick leave) from a workplace or school has been used to study the VR effects on respiratory infections. Illness absence rates reported in this study were in agreement with those from a prior study in London primary schools in 2005 to 2007, which found a 2.9 percent daily average prevalence of illness absence with no difference by gender, but slightly higher prevalence on Mondays and Fridays (Schmidt et al. 2010). Over 65 percent of illness absence in adults may be caused by respiratory infections (Bendrick 1998; Nichol et al. 1995). Milton et al. (2000) have speculated that the increased short-term sick leave they found in offices with lower VRs was from increased spread of respiratory disease, due to either increased airborne spread of infectious agents, or increased susceptibility related to increased indoor contaminants.

On the other hand, the associations found in the present study, in which longer averaging periods for VRs showed generally stronger associations with illness absence (1.4 percent, 1.6 percent, 1.7 percent, and 1.8 percent estimated reductions for 3 day, 7 day, 14 day, and 21 day averaged VR periods respectively), seem less compatible with a hypothesis of airborne infectious agents causing most illness absences and more suggestive of impacts from other exposures.

6.4.2 Strengths and Limitations of Study

This study demonstrates a new practical, cost-effective approach to studying the basic indoor parameters effects on large numbers of geographically dispersed indoor environments over extended time periods: using web-connected sensors to collect and transmit data in real time on CO_2, temperature, and relative humidity. Using this approach, data were collected allowing daily VR estimations in each of the over 160 classrooms for two school years, with minimal travel effort for researchers. Data on student attendance and demographics, in an unidentifiable form that did not require permission from all individual parents, was provided by participating school districts. This overall approach will allow collection of additional data from schools to investigate effects of indoor environments on occupants.

A key limitation in this approach was the periodic failure of the remote sensors, due to problems with the software. These sensor failures resulted in substantial data loss, but extending the study an additional unscheduled year provided substantial additional data. Another limitation was apparent inaccuracies in the CO_2 sensors, presumably from calibration drift over time. An automatic daily recalibration system in the sensors apparently failed to prevent drift problems, and then prevented post-correction. Indoor peak CO_2 values under 600 and over 7,000 ppm were considered to be implausible for an occupied classroom, and excluded them from analyses. Even exclusion of some true low or high values should not have biased estimated VR to illness absence relationships, but might have biased the existing VR summaries.

Another limitation is the identifying true indoor CO_2 equilibrium levels. Even with accurate real-time data from occupied environments, knowing if equilibrium has been reached through analyzing the large amounts of such data is difficult. If equilibrium levels are often not reached during a school day, they will be underestimated, which overestimates actual VRs. A VR-estimation algorithm was used that selected the maximum value of a daily 15-minute moving average peak value in each classroom as the estimated equilibrium concentration, to reduce the chance that peak recorded levels may have resulted from an occupant breathing on the sensor.

Finally, the outdoor CO_2 sensors intended for use in calculating delta CO_2 values provided data too erratic to use, which required estimation of all outdoor CO_2 values at a single value miscalculation of VRs. If some schools had consistently higher actual outdoor CO_2 values, such as from nearby roadway emissions, this scenario would lead to systematically low estimated ventilation rates from underestimated outdoor CO_2 levels.

The daily illness absence counts by classroom analyses produced data with very high proportions of zeros, posing a problem in identifying suitable statistical analysis models. Based on the understanding of the physical and biologic processes underlying the association between decreased VRs and increased illness absence, it was expected that a nonlinear relationship in which the absolute reduction in illness absence per unit change in VR decreased as VR levels increased. The model used may not fit this relationship.

The analysis collected more detailed data on classroom-level demographics than prior studies on this topic (Shendell et al. 2004). Obtaining individual-level linked data on demographics and absence would have allowed a more powerful analysis of individual-level, demographically adjusted incident disease analysis. This methodology would have required obtaining signed permissions from parents of all students in the approximately 160 classrooms, which would not have been feasible.

6.4.3 Implications

This study is the largest VR study reported to date with the most detailed measurements on the relationships between VRs in classrooms and illness absence in students. Although as an observational study it cannot establish causality, the findings are internally fairly consistent across school districts, climate zones, and ventilation types. The lack of statistical significance for findings in several districts seems, based on the consistency of the point estimates, to be due to limited sample sizes.

The relationships seen here and in several prior studies, if confirmed, would be consistent with a causal relationship between increasing VRs in elementary school classrooms and decreasing proportions of illness absence. These findings apply not only up to the current recommended VR levels (for an estimated 3.4 percent reduction in illness absence), but beyond them to at least 20 L/s per person (42 cfm/person, for an estimated 20.7 percent reduction in illness absence). Findings here suggest it would be beneficial to students, their families, and school districts to insure that VRs in elementary school classrooms substantially exceed current recommended ventilation guidelines. Additional data and analyses would be necessary to refine these estimates of benefit, and to produce estimates for other climates.

6.4.4 Conclusions

The majority of the California elementary school classrooms in this study provided their students with less outdoor air ventilation than specified in current State guidelines. Analyses in this study show that higher VRs in classrooms are associated consistently with decreased illness absence, although small sample sizes made this association less certain in some school districts. Keeping VRs below recommended levels in classrooms saves energy and money but may have large unrecognized costs due to increased health problems and illness absence among students. Increasing VRs *above* the recommended minimum levels, up to 20 L/s per person or higher, may further substantially decrease illness-related absences. The findings here suggest it may be beneficial to students, their families, and school districts to insure that VRs in elementary school classrooms substantially exceed current recommended ventilation guidelines.

CHAPTER 7:
Cost and Benefit Analyses Related to Different Levels of Classroom Ventilation Rates, Student Absence, and Energy Use

7.1 Background

In this chapter, several types of estimates related to VR and energy were developed. First, the estimated costs and benefits of increasing current ventilation rates in California K-12 classrooms were compared. The observed mean VR in L/s for California classrooms and the associated energy consumption and financial cost of ventilating all classrooms were estimated, assuming all classrooms were ventilated at the mean VR observed. Then the costs of increased energy consumption and related financial costs of several VR scenarios in California K-12 classrooms were estimated and compared to selected benefits related to decreased student absence (as estimated in Chapter 6). These scenarios are:

1) VRs increased from the mean observed VR to 7.1 L/s per person (15 cfm/person), the current Title 24 guideline levels; and
2) VRs raised from 7.1 L/s to 9.4 L/s per person (15 to 20 cfm/person).

The potential savings in energy and financial costs if classroom heating and cooling systems were operated only when necessary was also estimated. For example, from an hour before occupancy each day until an hour after occupancy ceases.

7.2 Methods

7.2.1 Comparing Costs and Benefits of Increasing Current Ventilation Rates in California K-12 Classrooms

For costs of energy use, the annual total (gas and electric) energy use and costs for California K-12 classrooms were estimated, and the increase in those costs required to increase the mean VR from the current level to 7.1 L/s per person, as specified in the California Title 24 ventilation standards, or to 9.4 L/s per person were also estimated. For information on the current California ventilation standards, see Appendix C.

The annual amounts of gas and electricity energy used to heat and cool ventilation air supplied to classrooms in California at the estimated existing mean ventilation rate were estimated using the following equations:

$$\Delta E = 0.58 \sum_i E_i \; F_{Ei} \qquad 7.2.1$$

$$\Delta G = 0.58 \sum_i G_i F_{Gi} V \qquad 7.2.2$$

where ΔE is the electricity use for cooling and dehumidifying ventilation air, E_i is the total classroom electricity use for California climate zone i, ΔG is the gas use for heating ventilation air, G_i is the total classroom gas use for climate zone *i*, F_i and G_i are the fractional change in total classroom electricity and gas use, respectively, use for each 1 L/s per person change in ventilation rate in climate zone *i*, and *V* is the estimated mean ventilation rate of classrooms in California in L/s per person. Values of E_i and G_i were obtained from the California Energy Use Survey (http://capabilities.itron.com/ceusweb/) and exclude colleges and universities, but include all school floor area (41.4 x 10^6 m^2), not just the area of classrooms. The coefficient of 0.58 is the ratio of classroom floor area to total floor area for California K-12 schools and yields estimates of energy use applicable to classrooms. The total classroom floor area was based on the product of the average classroom size (89 m^2) and the estimated 268,000 classrooms (Whitmore et al. 2003). Values of F_{Ei} and F_{Gi} were based on energy simulations (Benne et al. 2009) for the stock of education buildings in U.S. Department of Energy (DOE) climate zones 4B and 4C. Values of *F* for DOE climate zone 4C were applied to California climate zones FCZ01, FCZ05, FCZ08, and FCZ13, and values of *F* for DOE climate zone 4B were applied to the remaining California climate zones. Simulations show that the change in energy use with ventilation rate is approximately linear (Benne et al. 2009). Thus, the F_{Ei} and F_{Gi} values are not significantly coupled to the ventilation rate or the magnitude of change in ventilation rate. The calculation applies values of *F* determined for full schools to the classrooms that represent 58 percent of school floor area.

The value of V was calculated from a steady mass balance equation relating V with equilibrium indoor carbon dioxide concentration:

$$V = S/(C_{in} - C_{out}) \qquad 7.2.3$$

where

S is the carbon dioxide emission rate per student set equal to 0.0043 L/s (Haverinen-Shaughnessy et al. 2007),
C_{in} is the equilibrium indoor carbon dioxide concentration and
C_{out} is the outdoor carbon dioxide concentration.

As an estimate of C_{in}, the mean value of the one-hour average highest indoor carbon dioxide concentration from the California Classroom survey (Whitmore et al. 2003) was used. This survey was designed to provide data representative of the California building stock; thus, the ventilation rates based on the California Classroom Survey are likely to be more representative of the full stock of California classrooms than the ventilation rates obtained from the sample in the present study. The resulting estimated mean ventilation rate was 4.0 L/s per person.

The same basic equations were used to estimate the increase in gas and electricity use expected if the mean classroom ventilation rates were increased from the estimated current mean value of 4.0 L/s per person to 7.1 L/s per person as specified in Title 24, or to 9.4 L/s per person.

The associated annual gas and electricity costs were estimated by multiplying the energy use estimates by California-average gas and electricity prices for commercial building customers. The gas price was $0.028/kWh ($0.81 per therm) based on 2010 data from the Energy Information Agency (EIA), and the electricity price was $0.118/kWh based on data from December 2011 from the EIA.

To estimate benefits of resulting decreased illness absence from increased ventilation rates, the methods and results presented in Chapter 6 were utilized

7.2.2 Estimating Potential Savings in Energy and Financial Costs from Heating and Cooling Classroom Only When Necessary

Project objectives included developing estimates of the extent of unnecessary heating and cooling that takes place when classrooms are not occupied, and estimating the associated potential unnecessary energy use.

The available data for estimating the extent of unnecessary heating and cooling were the classroom schedules and the measured indoor and outdoor air temperatures. The classroom schedules indicate when students are present in the classrooms. No information was available on the additional times when only the teachers occupied classrooms. Heating and cooling periods during student occupancy in classrooms were classified as periods of necessary heating and cooling. In addition, any heating or cooling during the one-hour periods before and after student occupancy were counted as periods of necessary heating and cooling given the substantial probability that teachers occupied the classrooms during these periods. A period prior to student attendance is also often employed to preheat or precool the classroom before students arrive. Other periods of heating or cooling were classified as unnecessary; however, this characterization will result in some over-counting of unnecessary heating and cooling; for example, from periods when a teacher comes to work on a weekend and turns on the heating system.

Indoor and outdoor temperature data provide an indication of the periods of heating and cooling. Heating and cooling signs include the following:

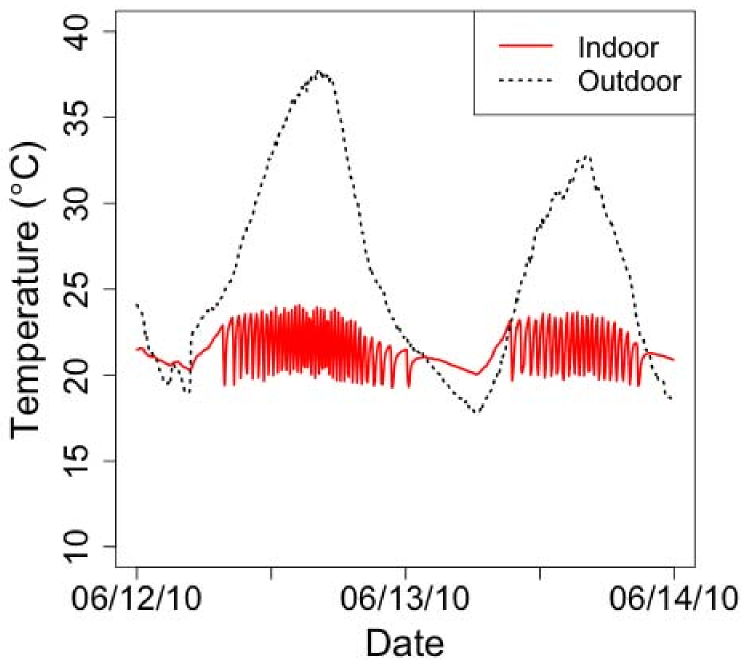
1. An indoor temperature maintained in the comfort zone, for example, 20 to 25 ^{o}C (68 to 77 ^{o}F) when it is substantially colder outdoors, for example, less than 14 ^{o}C (57 ^{o}F) suggests heating.
2. Maintenance of the indoor temperature in the comfort zone, for example, 20 to 25 ^{o}C (68 to 77 ^{o}F) when temperatures are higher outdoors than indoors suggests cooling.
3. An indoor temperature that does not follow the same time trend as the outdoor temperature (for example, increase or decrease with time) suggests heating or cooling.
4. An indoor temperature that is maintained in the comfort zone and that cycles up and down within a few-degree range (typical of thermostatically controlled systems) suggests heating or cooling.

Numerous factors complicate the analysis, leading to a substantial uncertainty in any estimation of the extent of unnecessary heating and cooling based on temperature data. For example, sunlight entering a window and operating lights and computers will heat a classroom when the heating system is turned off or reduce the need for heating when the system is operating. Also, the structure and content of classrooms absorb and release heat over time, causing time lags and dampening in indoor temperature trends relative to outdoor temperature trends. Classrooms vary in thermal mass (heat storage capacity), thermal insulation levels, heat release from lighting and computer equipment, and solar exposure. Manually controlled heating and cooling systems will not result in the same oscillation signal of thermostatically controlled systems. Errors in temperature measurements also cause uncertainties, considered small relative to the other sources of uncertainty. Some of these sources of uncertainty are diminished or eliminated during periods without occupancy; for example, there will be no manual control of heating or cooling, and rates of internal heat generation will generally be small, assuming that lights are off and computers are off or in sleep mode.

Algorithms were developed to automatically detect periods of unnecessary heating and cooling based on the signs indicated in paragraphs 1 and 4 listed above. When these algorithm results were inspected graphically, it was clear that none was sufficiently reliable; however, an algorithm based on the signs described in paragraph 4 appeared promising. Consequently, to provide a rough estimation of the extent of unnecessary heating and cooling, plots of both indoor and outdoor temperature versus time for all classrooms were visually inspected during all times when students did not occupy the classrooms. A full year of data was inspected for each classroom. The one-hour periods before and after student occupancy were neglected for the reasons described above. When the signs described in paragraphs 1 – 4 were satisfied, unnecessary heating and cooling were assumed to occur and the associated time periods tabulated. The mean values of indoor and outdoor temperatures for each of these periods were also calculated.

There is clearly a subjective element to the methodology used to define periods of unnecessary heating or cooling; however, the inspection-based procedure was judged more accurate than any fully automated algorithm that could be developed with the available resources. Figure 24 shows indoor and outdoor temperature data with an example of periods on two weekend days – between late morning and evening hours -- when the classroom was unoccupied but cooling was evident from the oscillations of indoor air temperature.

Figure 24: Example of Cyclic Oscillation in Indoor Air Temperature Data Indicating Space Cooling, During Two Weekend Days



The unnecessary annual energy use associated with periods of unnecessary heating and cooling was roughly estimated. The calculations used simple energy models to account for heat transfer through the building envelope and heat gain or loss from outdoor air ventilation.

The following equations were employed:

$$E_{UH} = (0.7/\varepsilon)\sum_i[\Delta t_i[1.8UA(T_{in}-T_o)_i) + AHN\rho C_p(T_{in}-T_o)_i]] + (0.3/COP_H)\sum_i[\Delta t_i[1.8UA(T_{in}-T_o)_i) + AHN\rho C_p(T_{in}-T_o)_i]] \qquad 7.2.4$$

$$E_{UC} = (1/COP_c)\sum_i[\Delta t_i[1.8UA\,(T_o-T_{in})_i + AHN\rho C_p(T_o-T_{in})_i]] \qquad 7.2.5$$

where:

E_{UH} = the unnecessary annual energy used for heating in the sample of 168 classrooms

ε = efficiency of a gas heating system, assumed to equal 0.75

Δt_i = the time elapsed during period *i* of unnecessary heating or cooling

U = the average overall thermal conductance (U value) of the classroom envelope

A = the classroom floor area

T_{in} = the average indoor temperature during period i

T_{out} = the average outdoor temperature during period i

H = the ceiling height, assumed to equal 3 m

N = the average air exchange rate of the classroom

ρ = the density of air at room temperature and atmospheric pressure equal to 1.2 kg m^{-3}

C_P = the specific heat of air at room temperature and atmospheric pressure equal to 1000 J kg^{-1} ^oC

E_{UC} = the unnecessary annual energy used for space cooling in the sample of 168 classrooms

COP_c = the coefficient of performance of the cooling system

COP_H = the coefficient of performance of the electric heating system, when heating is electric

In these equations, the terms containing *U* values account for heating or cooling energy needed to overcome heat conduction through the envelope and the terms containing an *N* (air exchange rate) account for heating or cooling energy needed to heat or cool ventilation air. The equations assume negligible internal heat generation when the classrooms are unoccupied (for example, lights and computers are off) and negligible solar heat gain, and do not account for heat storage in, or release from, the envelope or classroom contents. Also, the energy associated with dehumidification by air conditioning systems is neglected. Because classroom thermal and geometric characteristics were not collected, the calculations used an envelope *U* value of 0.5 W

m^{-2} °C, typical of an insulated wall constructed with 2 x 4 wood framing; the mean floor area of 89 m^2 from a survey of California classrooms (California Air Resources Board 2004); and an assumed ceiling height of 3 m. The floor area is multiplied by 1.8 to produce an estimate of the total area of the classroom envelope that connects to outdoors. This coefficient of 1.8 is based on the assumed ceiling height of 3 m, an assumed square floor (9.4 m by 9.4 m), and the assumption that the roof and, on-average, 2.5 walls connect to outdoors. Heat gain or loss through the classroom floor is neglected. For air exchange rate, the calculation used 1.3 air changes per hour , based on the average ventilation rate of 4 L/s per person in the California Classroom Survey as discussed previously, 25.3 students per classroom (from this study), and the classroom geometric characteristics described above. The coefficients of 0.7 and 0.3 are respectively the fraction of gas and electricity used to heat California schools from the California Energy Use Survey[9]. A value of 3.2 was assumed for COP_c corresponding to a Seasonal Energy Efficiency Ratio of approximately 12. A value of 2.2 was assumed for COP_H corresponding to a Heating Seasonal Performance Factor of 7.7.

For the full set of California classrooms, the unnecessary heating and cooling energy for the sample of 168 classrooms was multiplied by the estimated 303,400 K-12 grade classrooms in California[10] and divided by 168 to reach the average unnecessary heating and cooling energy usage per classroom. To estimate gas and electricity costs, gas and electricity energy use estimates were multiplied by the respective California-average gas and electricity prices for commercial building customers. The gas price was $0.028/kWh ($0.81 per therm) based on 2010 data from the Energy Information Agency (EIA) and the electricity price was $0.118/kWh based on data from December 2011 from the EIA.

7.3 Results

7.3.1 Comparing Costs and Benefits of Increasing Current Ventilation Rates in California K-12 Classrooms

7.3.1.1 Estimated Costs of Increasing Current Ventilation Rate in California K-12 Classrooms

Table 27 provides estimates of the annual energy used to heat and cool ventilation air supplied to California’s classrooms with the estimated mean existing ventilation rate of 4.0 L/s (8.5 cfm) per person. The incremental energy needed if mean ventilation rate was increased to 7.1 L/s (15 cfm) per person, as specified in Title 24, or to 9.4 L/s (20 cfm) per person, are also provided, along with estimated annual energy costs. For perspective, in parenthesis the energy consumed for ventilation is provided as a percentage of total building energy use. The calculations indicate that electricity used for ventilation in California classrooms is currently 1.5 percent of total classroom electricity use, while the gas used for ventilation is 5.2 percent of total classroom gas use. The associated annual energy costs are $3.5 million for electricity and $1.9 million for gas. Increasing the ventilation rate from 4.0 to 7.1 L/s (15 cfm) per person increases ventilation energy consumption and costs by 75 percent. Increasing the ventilation rate to 9.4 L/s (20 cfm) per person increases ventilation energy consumption and costs by 135 percent.

[9] http://capabilities.itron.com/ceusweb/

[10] http://www.cde.ca.gov/ls/fa/sf/facts.asp, accessed April 6, 2012

All of the estimates are expected to have a high level of uncertainty. Ventilation rates in the existing stock of schools are estimated based on data from only 67 schools, with data collected only one day per classroom. Also, the model-based estimates of how ventilation rates affect school energy use have not been verified experimentally. One cannot directly measure the energy used for ventilation because this energy is just a portion of total energy consumption of the classrooms heating, ventilating, and air conditioning system.

Table 27: Estimates of the Energy Use and Costs for Cooling and Heating the Ventilation Air Provided to Classrooms in California, and Potential Benefits, at Several Ventilation Rates**

	Energy Use		Costs			Benefits	
	Electricity (GWh) {% of total}*	**Gas (GWh) {% of total}^**	**Electricity Costs ($)**	**Gas Costs ($)**	**Total Increase in Energy Costs ($)**	**Increased State Revenue to School Districts ($)**	**Reduced Care-giving by Families ($)**
At existing ventilation rate of 4.0 L/s per person	29 {1.5}	68 {5.2}	3.5 M	1.9 M	0	0	0
From increasing ventilation rate from 4.0 to 7.1 L/s per person	22 {1.2}	52 {4.3}	2.6 M	1.4 M	4.0 M	33 M	80 M
From increasing ventilation rate from 4.0 to 9.4 L/s per person	40 {2.1}	92 {7.6}	4.7 M	2.6 M	7.3 M	66 M	160 M

Abbreviations: M, million;

** 6,224,000 students in 9,900 schools in 2009-10 (from http://www.cde.ca.gov/ls/fa/sf/facts.asp, accessed March 15, 2012)

*percentage of total classroom electricity use

^percentage of total classroom gas use

7.3.1.2 Estimating Benefits to School Districts of Decreased Illness Absence from Increased Ventilation Rates in California K-12 Classrooms

Based on the analyses performed, and other available data, in Chapter 6 it was estimated that for the approximately 6,224,000 students in California K-12 schools (in 9,900 schools in 2009-10) (http://www.cde.ca.gov/ls/fa/sf/facts.asp, accessed April 6, 2012), a decrease in illness-related absences by increasing the mean VRs from 4 to 7.1 L/s per person would increase annual state funding to school districts, under current formulas, by $33M (Table 27). Among this population, an increase in VR from 4 to 7.1 L/s per person would also produce benefits for families, from decreased costs for caregiver time, amounting to $80M. Total estimated benefits for this change in VRs equal $113M. A further increase from 7.1 to 9.4 L/s per person would increase annual state funding to school districts by an additional $33M, and increase benefits to families by an additional $880M, for an additional total benefit of $113M. Total benefits of increasing VRs from 4 to 7.1 L/s per person are estimated at $226M. Valuations of caregiver time include substantial subjectivity and uncertainty. The reduced costs in sick leave for teachers and staff, reductions in costs of medical care, or monetized improvements in quality of life for children were not estimated.

7.3.1.3 Comparing Costs and Benefits of Increased Ventilation Rates in California K-12 Classrooms

In comparing these estimated benefits of increased VRs to the estimated costs (Table 27), either of the two specific types of benefits estimated for increased classroom VRs substantially outweighs the estimated energy costs. Total estimated benefits from an increase in VRs from 4.0 to 7.1 L/s per person are $113M, over 28 times the estimated $4.0M incremental costs. Total benefits from an increase in VRs from 4.0 to 9.4 L/s per person, $226 million, are over 30 times the estimated additional energy costs of $7.3M. There are also other potential benefits not considered here for increased VRs in classrooms. There are likely to be other financial costs not considered here, as well as some potential increased health effects and costs, such as from increased intake of and indoor exposures to pollutants from outdoors.

If the magnitude of the relationships observed here and the costs and benefits estimates are confirmed, it would be advantageous and highly cost effective to the students, their families, and school districts to insure that VRs in elementary school classrooms substantially exceed current recommended ventilation guidelines. Additional data and analyses would be necessary to refine these estimates of cost and benefit.

7.3.2 Estimating Potential Savings in Energy and Financial Costs from Heating and Cooling Classroom Only When Necessary

Table 28 shows summary information from 168 classrooms. On average, unnecessary heating and cooling occurred for 32 hours and 13 hours per year per classroom, respectively. The extent of unnecessary cooling and heating varied greatly among classrooms; thus, the standard deviations were several times higher than the mean heating and cooling hours. Of the 168 classrooms, 21 percent had unnecessary heating and 22 percent had unnecessary cooling; however, 90 percent of the classrooms had 44 or fewer hours of unnecessary heating and 16 or fewer hours of unnecessary cooling. In a few classrooms, heating or cooling occurred during most of the unoccupied periods. In classrooms with unnecessary heating, this heating occurred

155 hours per year on average. In classrooms with unnecessary cooling, on average this cooling occurred 61 hours per year. The mean degree-hours of heating were almost four times larger than the mean degree-hours of cooling, because indoor-outdoor temperature differences are, on average, larger during the heating season.

Table 28: Summary Information from Analyses of Periods of Unnecessary Heating and Space Cooling

Parameter	Mean	Standard Deviation	Med-ian	Mini-mum	90th Percentile	Maxi-mum	Fraction >0*	Mean >0**
Heating Hours	32	186	0	0	44	2,079	0.21	155
Cooling Hours	13	74	0	0	16	730	0.22	61
Heating Degree-Hours (^{o}C –h)	579	3,850	0	0	542	47,377	---	2,777
Cooling Degree-Hours (^{o}C-h)	152	908	0	0	156	9,229	---	691

*fraction of classrooms with unnecessary heating or cooling
**mean value of parameter in classrooms with unnecessary heating or space cooling

Table 29 shows the energy consumption and energy costs estimates for unnecessary space heating and cooling, assuming the data from this study of three school districts are representative of the full set of grade K-12 schools in California. The estimated total energy costs for unnecessary heating and cooling are $1.5 million and $0.3 million, respectively, with a total cost of $1.8 million. The average annual cost per classroom is $6 for unnecessary heating and cooling. Total costs are highly influenced by substantial periods of unnecessary heating and cooling in a small fraction of all classrooms.

Table 29: Estimates Statewide Energy Use and Energy Costs from Unnecessary Heating and Cooling of Grade K-12 Classrooms

Parameter	Gas (kWh per year)	Electricity (kWh per year)	Gas $ per year	Electricity $ per year	Total $ per year
Unnecessary Heating	3.3×10^{7}	4.8×10^{6}	9.1×10^{5}	5.6×10^{5}	1.5×10^{6}
Unnecessary Space Cooling	--	2.9×10^{6}	--	3.4×10^{5}	3.4×10^{5}
Unnecessary Heating and Space Cooling	3.3×10^{7}	7.7×10^{6}	9.1×10^{5}	9.0×10^{5}	1.8×10^{6}

7.4 Discussion

7.4.1 Comparing Costs and Benefits of Increasing Current Ventilation Rates in California K-12 Classrooms

All three school districts in the studied classrooms had median daily VRs below the Title 24 minimum VR standard. Although providing classroom VRs below recommended levels in classrooms saves energy and money, the findings here suggest this strategy may have overriding but unrecognized costs of increased health problems and illness absence among students. The findings also suggest that increasing VRs *above* the recommended minimum levels, up to 20 L/s per person, may further substantially decrease illness absence. Total estimated benefits from an increase in VRs from 4.0 L/s to 7.1 L/s per person are $113M, over 28 times the estimated costs of $4.0M. Total benefits from an increase in VRs from 4.0 L/s to 9.4 L/s per person, $226 million, are over 30 times the estimated additional energy costs of $7.3M. Together, these findings suggest that increasing outdoor air ventilation in classrooms can provide a potentially large opportunity to improve the health and attendance of elementary school students in California in a highly cost effective way. These findings require replication and confirmation of causal connections.

The school study on which these estimates are based had limitations. Problems with failure of the CO_2 sensors, inaccuracies in the CO_2 data, and the difficulties of estimating true CO_2 equilibrium levels have been discussed in Chapter 6. These errors may have resulted in nonsystematic errors, or systematic overestimation of VRs, errors that are not likely to have created spurious relationships; instead, these errors may have reduced the apparent proportion of underventilated classrooms, underestimated true VR/illness absence relationships, and underestimated the range of VRs to which the findings apply. The estimates of energy costs, as already stated, are subject to substantial uncertainty. Nevertheless, very large errors would have been necessary to create the magnitude of differences seen between the estimated costs and benefits.

7.4.1.1 Implications

If the magnitude of the relationships observed, and the costs and benefits estimated are confirmed, it would be advantageous to students, their families, and school districts, and highly cost effective, to insure that VRs in elementary school classrooms substantially exceed current recommended ventilation guidelines. Additional data and analyses would be necessary to refine these estimates of cost and benefit, and to produce estimates for other climates.

A more efficient alternative to general dilution of indoor pollutants by outside air ventilation is reduction in the emissions of indoor contaminants. To the extent that relationships of VR and illness absence in schools are mediated by infectious respiratory agents from occupants, this is not easily done. Improved particle filtration, however, would be helpful for reducing airborne infectious agents, and often less energy intensive than increased ventilation. The pattern of findings here, however, with ventilation in periods immediately prior to a day of illness absence not being more strongly related than longer prior periods, does not seem to point to infectious agents as the key driver of this relationship. If other indoor contaminants such as chemicals are important, for instance by causing increased susceptibility to infectious agents, then reducing emission of these contaminants or reducing their indoor concentrations with suitable air cleaning systems may be feasible in lieu of increasing VR. Research is necessary to identify the causal agents associated with the influence of VRs on illness absence.

7.4.2 Estimating Potential Savings in Energy and Financial Costs from Heating and Cooling Classroom Only When Necessary

The energy consequences of unnecessary heating and cooling in classrooms estimates have a high uncertainty due to the factors identified in the description of the methodology; however, the estimated total annual energy costs are a modest $1.8 million per year, or $6 per classroom. A large fraction of total costs are the result of long periods of unnecessary heating and cooling in a small fraction of classrooms. Thus, it would be most cost effective to identify and take corrective measures in this small subset of classrooms. Periods of unnecessary heating and cooling can be identified through analyses of indoor and outdoor air temperatures over time; however, further work is needed to automate the methods of analysis.

7.5 Conclusions

The majority of the studied California elementary school classrooms in this study provided their students with less outdoor air ventilation than specified in current State guidelines, in some cases substantially less. If the magnitude of the relationships reported in Chapter 6 and the costs and benefit estimates described in this chapter are confirmed, it would be advantageous to students, their families, and school districts, and also highly cost effective (with benefits exceeding costs by more than a factor of 25), to insure that VRs in elementary school classrooms not only meet but substantially exceed current recommended ventilation guidelines. An alternative strategy of reducing emission of indoor pollutants, or removing them by air cleaning, depending on which pollutants are responsible for increased illness absence with lower VRs, may provide many of the benefits of increased ventilation.

The estimated total cost of energy used to condition unoccupied classrooms statewide is a modest $1.8 million, mostly for space heating. The average cost of wasted energy per classroom annually is under $10. Because a large fraction of the total costs are the result of long periods of unnecessary heating and cooling in a small fraction of classrooms, it would be most cost effective to identify and take corrective measures in this small set of classrooms.

GLOSSARY

A	the classroom floor area
ABV	absolute value
AC	air conditioned
ADA	actual daily attendance
AVG	average
BA	Bay Area
Cal.	Calibration
CI	confidence interval
COP_c	coefficient of performance of the cooling system
COP_H	coefficient of performance of the electric heating system, when heating is electric
CV	Central Valley
CZ	climate zone
C_{in}	mean value of the one-hour average highest indoor carbon dioxide concentration from the California Classroom survey
C_{max15}	maximum 15-minute moving average classroom carbon dioxide concentration
C_O	outside carbon dioxide concentration
C_P	specific heat of air at room temperature and atmospheric pressure
DCV	demand-controlled ventilation
DDC	direct digital control
DOE	U.S. Department of Energy
E_i	total classroom electricity use for California climate zone i
E_{UC}	unnecessary annual energy used for space cooling in the sample of 168 classrooms
E_{UH}	unnecessary annual energy used for heating in the sample of 168 classrooms
EIA	Energy Information Agency
F_i	the fractional change in total classroom electricity use for each 1 L/s per person change in ventilation rate in climate zone i
G_i	total classroom gas use for climate zone i
G_i	fractional change in total classroom gas use for each 1 L/s per person change in ventilation rate in climate zone i
H	ceiling height
HVAC	heating, ventilating, and air conditioning
IA	illness absence
IRR	incidence rate ratio
LEED	Leadership in Energy and Environmental Design
Manu.	manufacturer
Max	maximum
Min	minimum
M1	manufacturer 1
M2	manufacturer 2
M3	manufacturer 3

M4	manufacturer 4
M5	manufacturer 5
M6	manufacturer 6
M7	manufacturer 7
M8	manufacturer 8
N	carbon dioxide generation rate per person
NB	negative binomial
NHIS	National Health Interview Survey
NPV	net present value
OA	outdoor air
PCS	people counting system
PV	present value
R_i	revenue for student i
R_L	revenue limit
SC	South Coast
SD	standard deviation
T_{in}	average indoor temperature during period i
T_{out}	average outdoor temperature during period i
T1	type 1
T2	type 2
T3	type 3
T4	type 4
T5	type 5
U	average overall thermal conductance of the classroom envelope
V	estimated mean ventilation rate of classrooms in California
V_o	outdoor air flow rate per person
VR	ventilation rate
ZI	zero inflation
ZINB	zero inflated negative binomial
ΔE	electricity use for cooling and dehumidifying ventilation air
ΔG	gas use for heating ventilation air
Δt_i	the time elapsed during period i of unnecessary heating or cooling
ε	efficiency of gas heating system
ρ .	density of air at room temperature and atmospheric pressure

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APPENDIX A:
Primary Data from Evaluation of Accuracy of CO_2 Sensors

Table A-1: Data from Multiconcentration Calibration Checks of Sensor Accuracy

Build -ing	Slope	Zero Offset (ppm)	Linear Fit R^2	Error at 510 ppm (ppm)	Error at 760 ppm (ppm)	Error at 1010 ppm (ppm)	Manu- factur- er Code	Sen- sor Type	Self Cali- bra- tion	Sen- sor Age (yr))
-1	0.83	-55	0.99	-160	-196	-291	1	3	N	NA
-1	0.40	-113	0.68	-502	-756	-747	2	5	N	NA
-1	0.29	-77	0.76	-505	-717	-800	2	5	N	NA
-1	0.00	6	0.15	-502	-755	-1009	1	3	N	NA
-4	0.96	45	1.00	20	19	1	4	4	N	1
-4	0.93	49	1.00	18	-16	-2	4	4	N	1
-5	1.26	326	1.00	450	513	583	5	5	N	5
-5	1.01	-2	1.00	2	1	13	5	5	N	5
-5	1.14	-19	1.00	41	76	134	5	5	N	5
-6	0.96	31	1.00	10	-3	-11	4	1	Y	2
-6	0.91	45	1.00	7	-26	-44	4	1	Y	2
-6	1.08	-6	1.00	41	54	80	4	1	Y	2
-6	0.95	57	1.00	40	23	16	4	1	Y	2
-7	1.39	81	1.00	247	361	487	6	5	N	1
-7	0.91	39	1.00	-13	-26	-51	6	5	N	1
-8	0.93	21	1.00	-27	-30	-43	6	5	N	1
-9	0.97	18	1.00	-9	-1	-16	6	5	N	1
-9	0.87	56	1.00	-11	-48	-72	6	5	N	1
1	0.71	245	0.98	104	23	-99	4	4	N	0.5
1	0.69	195	0.99	53	-61	-135	4	4	N	0.5
1	0.79	60	0.99	-19	-126	-174	4	4	N	0.5
1	0.85	39	0.97	6	-81	-177	4	4	N	0.5
1	0.51	367	0.89	148	-19	-210	4	4	N	0.5
3	2.66	-534	1.00	319	697	1146	7	4	N	1
3	1.39	105	0.94	213	401	609	7	4	N	1
3	1.44	-119	0.99	152	157	284	7	4	N	1
3	1.50	-136	0.96	-507	180	399	7	4	N	1
3	1.52	-171	0.98	5	277	420	7	4	N	1
3	1.60	-237	0.91		95	467	7	4	N	1
4	0.98	44	1.00	24	38	19	7	4	N	5
4	0.87	38	0.99	-50	-58	-87	7	4	N	5
4	0.92	28	1.00	-22	-41	-38	7	4	N	5
4	0.90	-18	1.00	-64	-107	-91	7	4	N	5
4	0.94	35	1.00	-7	-6	-14	7	4	N	5
4	0.80	-139	1.00	-247	-300	-320	7	4	N	5
4	0.79	-173	1.00	-294	-324	-376	7	4	N	5

Table A-1: Data from Multiconcentration Calibration Checks of Sensor Accuracy (Continued)

Build-ing	Slope	Zero Offset (ppm)	Linear Fit R^2	Error at 510 ppm (ppm)	Error at 760 ppm (ppm)	Error at 1010 ppm (ppm)	Manu-factur-er Code	Sen-sor Type	Self Cali-bra-tion	Sen-sor Age (yr))
5	1.14	-26	1.00	41	86	126	4	4	N	4
5	1.02	29	1.00	33	47	59	4	4	N	4
5	0.96	57	1.00	31	37	24	4	4	N	4
5	0.95	36	1.00	2	1	-15	4	4	N	4
6	0.88	114	1.00	36	36	28	4	1	Y	3.5
6	0.93	69	1.00	22	25	20	4	1	Y	3.5
6	0.91	97	1.00	38	30	25	4	1	Y	3.5
6	0.84	-68	1.00	-152	-187	-239	4	1	Y	3.5
6	0.93	107	0.99	70	30	83	4	1	Y	3.5
6	0.92	60	1.00	27		-24	4	1	Y	3.5
6	0.92	75	1.00	24	22	18	4	1	Y	3.5
6	0.90	119	1.00	74	36	14	4	1	Y	3.5
6	0.86	105	1.00	24	13	-21	4	1	Y	3.5
6	0.90	75	1.00	19	7	-23	4	1	Y	3.5
6	0.92	74	1.00	18	23	7	4	1	Y	3.5
7	1.01	16	1.00	14	31	39	4	1	Y	7
7	1.06	-226	1.00	-195	-182	-171	4	1	Y	7
7	1.04	119	1.00	126	164	174	4	1	Y	7
7	0.97	32	1.00	19	11	5	4	1	Y	7
16	0.95	-4	0.94	42	-51	-212	5	2	Y	1.5
16	0.81	105	0.98	14	-59	-104	5	2	Y	1.5
17	0.98	-48	0.98	-1	-159	-57	5	2	Y	1.5
17	0.92	39	0.95	92	-151	-27	5	2	Y	1.5
17	0.96	-35	0.95	36	-201	-55	5	2	Y	1.5
17	0.92	3	0.98	-11	-141	-41	5	2	Y	1.5
17	0.93	-18	0.98	-19	-148	-71	5	2	Y	1.5
17	0.98	-21	0.98	19	-121	-47	5	2	Y	1.5
17	1.02	-70	0.99	-5	-134	-40	5	2	Y	1.5
17	1.00	-46	0.98	1	-130	-28	5	2	Y	1.5
17	1.03	-44	0.99	13	-105	-2	5	2	Y	1.5
17	0.99	-65	0.99	-31	-143	-47	5	2	Y	1.5
17	1.02	-60	0.99	0	-126	-9	5	2	Y	1.5
17	1.01	-60	0.99	-4	-125	-35	5	2	Y	1.5
17	1.03	-72	0.99	-8	-133	-19	5	2	Y	1.5
17	1.04	-52	0.98	24	-109	30	5	2	Y	1.5
17	0.99	-28	0.99	11	-112	-2	5	2	Y	1.5

Table A-1: Data from Multiconcentration Calibration Checks of Sensor Accuracy (Continued)

Build -ing	Slope	Zero Offset (ppm)	Linear Fit R^2	Error at 510 ppm (ppm)	Error at 760 ppm (ppm)	Error at 1010 ppm (ppm)	Manu- factur- er Code	Sen- sor Type	Self Cali- bra- tion	Sen- sor Age (yr))
21	0.89	59	1.00	21	-9	-111	5	5	Y	4
21	0.83	182	0.99	50	97	56	5	5	Y	4
21	0.89	89	1.00	54	14	-46	5	5	Y	4
21	0.94	64	1.00	31	37	-19	5	5	Y	4
21	0.86	93	1.00	19	-14	-44	5	5	Y	4
21	0.95	39	1.00	6	20	-30	5	5	Y	4
21	0.90	57	1.00	15	-34	-43	5	5	Y	4
21	0.77	110	1.00	-10	-58	-120	5	5	Y	4
23	0.94	30	1.00	-3	-13	-31	1	1	Y	3
23	1.05	-17	1.00	7	24	35	1	1	Y	3
24	0.95	-35	1.00	73	71	78	5	1	Y	1
24	0.95	-26	1.00	41	78	74	5	1	Y	1
24	0.94	-28	1.00	61	87	91	5	1	Y	1
24	0.99	-21	1.00	29	29	21	5	1	Y	1
24	0.99	-19	1.00	25	23	20	5	1	Y	1
25	0.88	16	1.00	-46	-86	-90	7	4	N	1
25	0.97	115	1.00	76	81	133	7	4	N	1
25	0.93	69	1.00	31	11	-3	7	4	N	1

Table A-2: Data from Single-Concentration Calibration Checks of Sensor Performance

Building	Error (ppm)	Manufacturer Code	Sensor Type	Self Calibration	Sensor Age (yr)
-2	58	3	5	N	4
-2	38	3	5	N	4
-2	341	3	5	N	4
-2	48	3	5	N	4
-2	540	3	5	N	4
-2	-378	3	5	N	4
-2	215	3	5	N	4
-2	-371	4	5	N	NA
-2	662	3	5	N	4
-2	89	3	5	N	4
-2	668	3	5	N	4
-2	1013	3	5	N	4
-2	363	3	5	N	4
-2	-103	3	5	N	4
-2	452	3	5	N	4
-2	621	3	5	N	4
-2	437	3	5	N	4
-2	-342	3	5	N	4
-2	469	3	5	N	4
-2	85	3	5	N	4
-3	292	5	5	N	NA
-3	276	5	5	N	NA
-3	133	5	5	N	NA
-4	78	4	4	N	1
-6	92	4	1	Y	2
2	69	4	1	Y	5
2	156	4	1	Y	5
2	76	4	1	Y	5
2	258	4	1	Y	5
2	1	4	1	Y	5
2	97	4	1	Y	5
2	-20	4	1	Y	5
2	258	4	1	Y	5
2	13	4	1	Y	5
4	-68	7	4	N	5
4	-1298	7	4	N	5
8	65	11	5	N	5
8	64	11	5	N	5
9	59	11	5	N	5
9	61	11	5	N	5
9	47	11	5	N	5
9	57	11	5	N	5
10	64	11	5	N	5
10	68	11	5	N	5

Table A-2: Data from Single-Concentration Calibration Checks of Sensor Performance (Continued).

Building	Error (ppm)	Manufacturer Code	Sensor Type	Self Calibration	Sensor Age (yr)
11	35	5	1	Y	2
11	-310	5	1	Y	2
11	40	5	1	Y	2
11	33	5	1	Y	2
11	-80	5	1	Y	2
11	-1	5	1	Y	2
11	25	5	1	Y	2
12	33	5	2	Y	1
12	26	5	2	Y	1
12	37	5	2	Y	1
12	31	5	2	Y	1
12	65	5	2	Y	1
13	200	7	4	N	1
13	76	7	4	N	1
13	161	7	4	N	1
14	30	8	5	Y	3
14	858	8	5	Y	3
14	67	8	5	Y	3
14	98	8	5	Y	3
14	-14	8	5	Y	3
14	185	8	5	Y	3
14	307	8	5	Y	3
14	530	8	5	Y	3
14	197	8	5	Y	3
14	94	8	5	Y	3
14	86	8	5	Y	3
14	811	8	5	Y	3
14	185	8	5	Y	3
14	336	8	5	Y	3
15	35	9	5	Y	1
15	19	9	5	Y	1
15	30	9	5	Y	1
15	59	9	5	Y	1
15	131	9	5	Y	1
15	119	9	5	Y	1
15	-31	10	1	Y	1
15	-9	10	1	Y	1
18	95	10	1	Y	1
19	-25	4	1	Y	3
19	255	4	1	Y	3

Table A-2: Data from Single-Concentration Calibration Checks of Sensor Performance (Continued).

Building	Error (ppm)	Manufacturer Code	Sensor Type	Self Calibration	Sensor Age (yr)
20	-389	4	5	N	13
20	-415	1	3	N	13
20	-397	4	5	N	13
20	22	4	5	N	13
20	5	4	5	N	13
20	-572	4	5	N	13
20	-429	1	3	N	13
20	-434	4	5	N	13
20	1486	4	5	N	13
20	-413	1	3	N	13
20	10	4	5	N	13
20	-4	4	5	N	13
20	48	4	5	N	13
20	-134	1	3	N	13
20	119	1	3	N	13
20	-9	4	5	N	13
20	51	1	3	N	13
20	154	1	3	N	13
20	25	4	5	N	13
20	168	1	3	N	13
20	551	4	5	N	13
20	124	1	3	N	13
21	151	5	5	N	0.5
22	184	11	5	N	7
22	-67	11	5	N	7
22	552	11	5	N	7
22	45	11	5	N	7
22	545	11	5	N	7
22	116	11	5	N	7
22	226	11	5	N	7
22	378	11	5	N	7
22	97	11	5	N	7
25	10	7	4	N	0.5
25	29	7	4	N	0.5

APPENDIX B:
Excerpts from Specifications for Demand-Controlled Ventilation in Title 24 and Its Appendices

Section 121 – Requirements for Ventilation

All nonresidential, high-rise residential, and hotel/motel occupancies shall comply with the requirements of Section 121(a) through 121(e).

……

(a) **General Requirements.**

1. All enclosed spaces in a building that are normally used by humans

Required Demand Control Ventilation. HVAC systems with the following characteristics shall have demand ventilation controls complying with 121(c)4:

A. They have an air economizer; and

B. They serve a space with a design occupant density, or a maximum occupant load factor for egress purposes in the CBC, greater than or equal to 25 people per 1000 ft2 (40 square foot per person); and

C. They are either:

i. Single zone systems with any controls; or

ii. Multiple zone systems with Direct Digital Controls (DDC) to the zone level.

EXCEPTION 1 to Section 121(c)3: Classrooms, call centers, office spaces served by multiple zone systems that are continuously occupied during normal business hours with occupant density greater than 25 people per 1000 ft^2 per Section 121(b)2B, healthcare facilities and medical buildings, and public areas of social services buildings are not required to have demand control ventilation.

EXCEPTION 2 to Section 121(c)3: Where space exhaust is greater than the design ventilation rate specified in Section 121(b)2B minus 0.2 cfm per ft^2 of conditioned area**.**

EXCEPTION 3 to Section 121(c)3: Spaces that have processes or operations that generate dusts, fumes, mists, vapors, or gases and are not provided with local exhaust ventilation, such as indoor operation of internal combustion engines or areas designated for unvented food service preparation, or beauty salons shall not install demand control ventilation.

EXCEPTION 4 to Section 121(c)3: Spaces with an area of less than 150 square feet, or a design occupancy of less than 10 people per Section 121(b)2B.

4. **Demand Control Ventilation Devices.**

A. For each system with demand control ventilation, CO_2 sensors shall be installed in each room that meets the criteria of Section 121(c)3B with no less than one sensor per 10,000 ft^2 of floor space. When a zone or a space is served by more than one sensor, signal from any sensor indicating that CO_2 is near or at the set point within a space, shall trigger an increase in ventilation to the space; B. CO_2 sensors shall be located in the room between 3 ft. and 6 ft. above the floor or at the anticipated height of the occupants heads;

SECTION 121 – REQUIREMENTS FOR VENTILATION

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C. Demand ventilation controls shall maintain CO_2 concentrations less than or equal to 600 ppm plus the outdoor air CO_2 concentration in all rooms with CO_2 sensors;

EXCEPTION to Section 121(c)4C: The outdoor air ventilation rate is not required to be larger than the design outdoor air ventilation rate required by Section 121(b)2 regardless of CO_2 concentration.

D. Outdoor air CO_2 concentration shall be determined by one of the following:

i. CO_2 concentration shall be assumed to be 400 ppm without any direct measurement; or

ii. CO_2 concentration shall be dynamically measured using a CO_2 sensor located within 4 ft. of the outdoor air intake.

E. When the system is operating during hours of expected occupancy, the controls shall maintain system outdoor air ventilation rates no less than the rate listed in TABLE 121-A times the conditioned floor area for spaces with CO_2 sensors, plus the rate required by Section 121(b)2 for other spaces served by the system, or the exhaust air rate whichever is greater;

F. CO_2 sensors shall be certified by the manufacturer to be accurate within plus or minus 75 ppm at a 600 and 1000 ppm concentration when measured at sea level and 25°C, factory calibrated or calibrated at start-up, 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 121(b)2 to the zone serviced by the sensor at all times that the zone is occupied.

G. The CO_2 sensor(s) reading for each zone shall be displayed continuously, and shall be recorded on systems with DDC to the zone level.

Section 125 – Required Nonresidential Mechanical System Acceptance

(a) Before an occupancy permit is granted the following equipment and systems shall be certified as meeting the Acceptance Requirements for Code Compliance, as specified by the

Reference Nonresidential Appendix NA7. A Certificate of Acceptance shall be submitted to the enforcement agency that certifies that the equipment and systems meet the acceptance requirements:

……

5. Demand control ventilation systems required by Section 121(c)3 shall be tested in accordance with NA7.5.5

……

NA7.5.5 Demand Control Ventilation Systems

NA7.5.5.1 Construction Inspection

Prior to Functional Testing, verify and document the following:

• Carbon dioxide control sensor is factory calibrated or field-calibrated per §121(c)4.

• The sensor is located in the high density space between 3 ft. and 6 ft. above the floor or at the anticipated level of the occupants' heads.

• demand-controlled ventilation control set point is at or below the CO_2 concentration permitted by §121(c)4C.

NA7.5.5.2 Functional Testing

Step 1: Disable economizer controls

Step 2: Simulate a signal at or slightly above the CO_2 concentration set point required by §121(c)4C. Verify and document the following:

• For single zone units, outdoor air damper modulates open to satisfy the total ventilation air called for in the Certificate of Compliance.

• For multiple zone units, either outdoor air damper or zone damper modulate open to satisfy the zone ventilation requirements.

Step 3: Simulate signal well below the CO_2 set point. Verify and document the following:

• For single zone units, outdoor air damper modulates to the design minimum value.

• For multiple zone units, either outdoor air damper or zone damper modulate to satisfy the reduced zone ventilation requirements.

Step 4: Restore economizer controls and remove all system overrides initiated during the test.

Step 5: With all controls restored, apply CO_2 calibration gas at a concentration slightly above the set point to the sensor. Verify that the outdoor air damper modulates open to satisfy the total ventilation air called for in the Certificate of Compliance.

APPENDIX C:
Current Ventilation Standards Per State of California and ASHRAE

2008 Building Energy Efficiency Standards

CALIFORNIA CODE OF REGULATIONS, TITLE 24, Part 6

SUBCHAPTER 3: SECTION 121 – REQUIREMENTS FOR VENTILATION, p. 73.

(b) **Design Requirements for Minimum Quantities of Outdoor Air**. Every space in a building shall be designed to have outdoor air ventilation according to Item 1 or 2 below:

> 1. **Natural ventilation**. A. Naturally ventilated spaces shall be permanently open to and within 20 feet of operable wall or roof openings to the outdoors, the openable area of which is not less than 5 percent of the conditioned floor area of the naturally ventilated space. Where openings are covered with louvers or otherwise obstructed, openable area shall be based on the free unobstructed area through the opening. . . .
>
> 2. **Mechanical ventilation**. Each space that is not naturally ventilated under Item 1 above shall be ventilated with a mechanical system capable of providing an outdoor air rate no less than the larger of: A. The conditioned floor area of the space times the applicable ventilation rate from TABLE 121-A (of 0.15 cfm/ft2); or B. 15 cfm per person times the expected number of occupants.

Source: http://www.energy.ca.gov/2008publications/CEC-400-2008-001/CEC-400-2008-001-CMF.PDF

Accessed April 14, 2012

<u>Note</u>: this California ventilation standard for classrooms is between the two default ASHRAE standards applicable to elementary school classrooms (Table A1-1.)

Table C-1: ASHRAE Ventilation Rate Requirements (ASHRAE 2010, P. 12)

	ASHRAE 62.1-2010		
Space Use	**VR/person**	**VR/area**	**Overall, at specific assumed occupant density**
Classrooms (ages 5-8)	5 L/s-person (10 cfm/person)	0.6 L/s-m2 (0.12 cfm/ft2)	7.4 L/s per person* {assumed 25 persons/100 m^2} (15 (14.8)cfm/person)* {assumed 25 persons/1000 ft^2}
Classrooms (ages 9+)	5 L/s-person (10 cfm/person)	0.6 L/s-m2 (0.12 cfm/ft2)	6.7 L/s per person ** {assumed 35 persons/100 m^2} (13 (13.4) cfm/person)** {assumed 35 persons/1000 ft^2}

* assumed classroom occupant density =25 persons/100 m^2 or /1,000 ft^2

** assumed classroom occupant density = 35 persons/100 m^2 or /1,000 ft^2, but 100 m^2 =1,076 ft^2

(Note: Children in third grade are usually age 8 or 9 (but sometimes 7. Children in 4th and 5th grades will usually be ages 9+.)

APPENDIX D:
Calculations for Comparisons to Findings of Shendell et al. (2004).

Shendell et al. (2004) reported that higher classroom VRs were associated with a substantial reduction in student absence: a decrease of 1,000 ppm in indoor minus outdoor CO_2 concentrations (ΔCO_2) within the observed range of 10-4,200 ppm was associated with a 10 percent to 20 percent relative decrease (0.5-0.9 percent absolute decrease) in *total* student absence (which averaged 5.0 percent). This equals a 1 percent to 2 percent relative decrease (0.05-0.09 percent absolute decrease) in total student absence per decrease of 100 ppm ΔCO_2. This in turn is equivalent (http://www.iaqscience.lbl.gov/si/vent-absences.html) to a relative decrease of 1-4 percent (absolute decrease of 0.05-1.8 percent) in total absence, per each additional 1 L/s per person in VR within the range of 2.5-15 L/s per person. Assuming that all this decrease in total absence is within illness absence rather than in other types of absence, and that the mean illness absence is the 2.35 percent observed in the present study, the 0.05-0.18 percent absolute decrease in illness absence is then an estimated 2-8 percent relative decrease in illness absence, per VR increase of 1 L/s per person, in the range of 2.5-15 L/s per person.

This estimated finding of an equivalent 2 to 8 percent relative decrease in illness absence per VR increase of 1 L/s per person is approximately 1.3-7 times larger than the findings in the present study of a 1.2 to 1.5 percent relative decrease.