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A PILOT STUDY OF THE ACCURACY OF CO₂ SENSORS IN COMMERCIAL BUILDINGS

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ABSTRACT

Carbon dioxide (CO₂) sensors are often deployed in commercial buildings to obtain CO₂ data that are used to automatically modulate rates of outdoor air supply. The goal is to keep ventilation rates at or above design requirements and to save energy by avoiding ventilation rates exceeding design requirements. However, there have been many anecdotal reports of poor CO₂ sensor performance in actual commercial building applications. This study evaluated the accuracy of 44 CO₂ sensors located in nine commercial buildings to determine if CO₂ sensor performance, in practice, is generally acceptable or problematic. CO₂ measurement errors varied widely and were sometimes hundreds of parts per million. Despite its small size, this study provides a strong indication that the accuracy of CO₂ sensors, as they are applied and maintained in commercial buildings, is frequently less than needed to measure typical values of maximum one-hour-average indoor-outdoor CO₂ concentration differences with less than a 20% error. Thus, we conclude that there is a need for more accurate CO₂ sensors and/or better sensor maintenance or calibration procedures.

INTRODUCTION

People produce and exhale carbon dioxide (CO₂) as a consequence of their normal metabolic processes; thus, the concentrations of CO₂ inside occupied buildings are higher than the concentrations of CO₂ 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 with fair accuracy from the maximum steady state difference between indoor and outdoor CO₂ concentrations (ASTM 1998, Persily 1997). For

example, under steady conditions, if the indoor CO₂ concentration in an office work environment is 700 parts per million above the outdoor concentration, the ventilation rate is approximately 15 cfm per person (ASHRAE 2001). In many real buildings, occupancy and ventilation rates are not stable for sufficient periods to enable an accurate determination of ventilation rate from CO₂ data; however, CO₂ concentrations remain an approximate and easily measured surrogate for ventilation rate. The difference between the indoor and outdoor CO₂ concentration is also an indicator of the indoor concentrations of other occupant-generated bioeffluents, such as body odors (ASHRAE 2001).

Epidemiological research has found that indoor CO₂ 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 CO₂ concentration have, on average, increased sick building syndrome health symptoms (Seppanen et al. 1999). In a study within a jail, higher CO₂ concentrations were associated with increased respiratory disease (Hoge et al 1994) and higher CO₂ concentrations in schools have been associated with increased student absence (Shendell et. al 2004). Shaughnessy et al. (2007) found poorer student performance on standardized academic performance tests correlated with increased CO₂ in classrooms and Wargocki and Wyon (1996) found that students performed various school-work tasks less rapidly or less accurately when the classroom CO₂ concentration was higher.

In a control strategy called demand controlled ventilation (Fisk and de. Almeida 1998, Emmerich and Persily 2001), CO₂ sensors, sometimes called CO₂ transmitters, are often used in commercial buildings to obtain CO₂ data that are used to automatically modulate rates of outdoor air supply. The goal is to keep ventilation rates at or above design requirements but to also adjust the outside air supply rate with changes in occupancy in order to save energy by avoiding

over-ventilation relative to design requirements. Some buildings use CO₂ sensors just to provide feedback about ventilation rates to the building operator, without automatic modulation of ventilation rates based on the measured CO₂ concentrations.

Reviews of the research literature on demand controlled ventilation (Apte 2006, Emmerich and Persily 2001, Fisk and de Almeida 1998) indicate a significant potential for energy savings, particularly in buildings or spaces with a high and variable occupancy. Based on recent modeling, Brandemuehl and Braun (1999), cooling energy savings from application of demand controlled ventilation are as high as 20%. However, there have been many anecdotal reports of poor CO₂ sensor performance in actual applications of demand controlled ventilation. In a presentation by the Iowa Energy Center¹ on a laboratory-based intercomparison of three CO₂ sensors over time, the measured concentrations of different sensors varied by as much as 265 ppm.

Based on the prior discussion, there is a good justification for monitoring indoor CO₂ concentrations and using these concentrations to modulate rates of outdoor air supply. However, this strategy will only be effective if CO₂ sensors have a reasonable accuracy in practice. The objective of this study was; therefore, to gain some initial data on the performance of CO₂ sensors in field settings to determine if CO₂ sensor performance, in practice, is generally acceptable or problematic.

METHODS

Two different protocols were employed to assess the accuracy of 44 CO₂ sensors located in 9 buildings within California. When possible, we used bags of CO₂ calibration gases to

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evaluate sensor performance at five CO₂ concentrations from 236 to 1180 parts per million (ppm). Based on the specifications of the calibration gas supplier and the protocols employed, the calibration gas concentrations were known within about 7% at the lowest concentration and within 2% at the highest concentration. In the multi-point calibration checks, the CO₂ sensors located in buildings sampled each of the calibration gases. The CO₂ concentrations reported on the computer screen of the building's data acquisition system or on the CO₂ sensor display were recorded². The data obtained were processed to obtain an offset error and slope or sensor gain error using a least-squares linear regression of measured CO₂ concentration versus "true" CO₂ concentration. If a sensor agreed exactly with the "true" concentration, then the offset error would be 0 and the slope equal unity. However, an offset error of 50 ppm would indicate that the sensor would read 50 ppm high at a concentration of 0 ppm. A slope of 0.75 would indicate that slope of curve of reported concentration plotted versus true concentration is 0.75. We employed these multipoint calibrations when the CO₂ 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 were provided with sufficient frequency (e.g., 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 18 sensors from six buildings.

When a multi-point calibration was not possible, we performed a single-point calibration check of the building's CO₂ sensors using a co-located and calibrated reference instrument. The protocol was very simple. A research-grade CO₂ instrument was calibrated, taken to the building, and placed so that it sampled at the same location as the building's CO₂ sensor. Data from the reference instrument was logged over time. CO₂ concentrations reported on the

² In three buildings, the CO₂ concentrations on the CO₂ sensor's display were used, but in all cases we confirmed that the building's data acquisition system reported the same CO₂ concentration as the sensor display.

sensor's display or the building's data acquisition system's screen were recorded manually. The data were processed to obtain an absolute error, equal to the CO₂ concentration reported by the building's data acquisition system minus the true CO₂ concentration. We also calculated a percentage error equal to the absolute error divided by the true CO₂ concentration, multiplied by 100%. This type of sensor performance check was completed for 37 sensors located in seven buildings, including single point calibration checks in a few buildings where multi-point calibrations were completed. One limitation of the single point calibration data is that all of these data were obtained at low CO₂ concentrations of 470 ppm or less.

The reference 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 % of span concentration but limited by the accuracy of the calibration gas mixture". In our study, the span gas concentration was 2356 ppm and rated at $\pm 2\%$ accuracy. We also performed a multipoint calibration check of this reference instrument during six field site visits. The offset errors indicated by these calibration checks ranged from -18 to $+17$ ppm. The calibration slopes were 1.01 or 1.02 in five calibration checks and equaled 0.96 in the sixth calibration check (R^2 equaled 1.00 in all calibration checks). Additionally, at one time, this instrument was intercompared with another research grade, but less accurate, CO₂ instrument. In the four point intercomparison, the deviations ranged from -27 to $+33$ ppm with corresponding percentage errors of -1.9 to $+4.9\%$. Finally, we used the calibrated reference instrument to measure the CO₂ concentrations in two cylinders of CO₂ calibration gas that were not employed in instrument's calibration. In these two measurements, the reported CO₂ concentration was approximately 30 ppm less than indicated on the calibration gas cylinders. Altogether, these tests imply that the uncertainty in our reference CO₂ measurements was about ± 30 ppm.

All of the CO₂ sensors evaluated were non dispersive infrared sensors with a default measurement range of zero to 2000 ppm, although in some cases other ranges could be selected. The manufacturers' accuracy specifications ranged from ± 40 ppm $\pm 3\%$ of reading to ± 100 ppm over 5 years. Some sensors have a dual wavelength system detect and control for calibration drift, some used a single wavelength sensor and corrected for calibration drift with an algorithm assuming that the minimum measured concentration equals a reference value (e.g., 400 ppm). Most sensors sampled via diffusion, i.e., had no sample pump. The manufacturers' recommended calibration frequency ranged from every six months to every five years.

The sensor performance checks were all performed in commercial buildings located in California, selected without consideration of building age or type of CO₂ sensor. The buildings were used for healthcare, education, software industry, judicial, and state office applications. There were six brands of CO₂ sensors³ and multiple model types of some brands.

RESULTS

Multi-point Calibration Checks

Table 1 and Figure 1 provide results from the multi-point calibration checks of CO₂ sensors. Offset errors ranged from -113 to $+326$ ppm. For 14 of 18 sensors, the offset error was less than 75 ppm. The slope of the curve of measured versus true CO₂ concentration ranged from 0 to 1.35. For 8 of 18 sensors, the slope was within 0.05 of unity. Based on the offset error and slope, Table 1 provides predicted CO₂ concentration measurement errors at true CO₂ concentrations of 600 and 1000 ppm. At 600 ppm, predicted errors ranged from -594 ppm to $+537$ ppm. For 11 of 18 sensors, the predicted error at 600 ppm was less than 100 ppm. The

³ Some manufacturers do not make their own sensors, they market sensors from other manufacturers.

accuracy of sensors of the same brand was highly variable. There were not sufficient data to draw conclusions about the trend in sensor accuracy with a sensor age.

Table 1. Results of multi-point calibration checks of CO₂ sensors.

Build-ing	Sensor Code	Offset Error (ppm)	Slope	R ²	Predicted Error at 600 ppm (ppm)	Predicted Error at 1000 ppm (ppm)	Reported Sensor Age (years)	Sensor Manufacturer Code
1	Unit 1-1*	-55	0.89	0.99	-119	-161	--	1
1	Unit 2-1*	-113	0.43	0.68	-454	-681	--	2
1	Unit 2-2*	-77	0.32	0.76	-488	-762	--	2
1	Unit 2-3*	6	0.00	0.15	-594	-994	--	1
4	1015	45	1.03	1.00	62	73	1	4
4	1016	49	1.00	1.00	49	50	1	4
5	Circle	326	1.35	1.00	537	678	5	5
5	Triangle	-2	1.09	1.00	51	86	5	5
5	Square	-19	1.23	1.00	117	207	5	5
6	Courtroom 1	32	1.03	1.00	50	62	2	4
6	Courtroom 3	45	0.98	1.00	31	22	2	4
6	Courtroom 4	-6	1.16	1.00	91	155	2	4
6	Courtroom 5	57	1.03	1.00	73	84	2	4
7	Classroom 110	81	1.50	1.00	381	581	1	6
7	Classroom 127	39	0.98	1.00	26	18	1	6
8	Library 232	21	1.00	1.00	24	26	1	6
9	AHU 2	18	1.04	1.00	42	58	1	6
9	AHU 1	56	0.94	1.00	20	-5	1	6

*sensor pump not working, calibration gas pushed through sensor

Note: R² is the square of the Pearson correlation coefficient

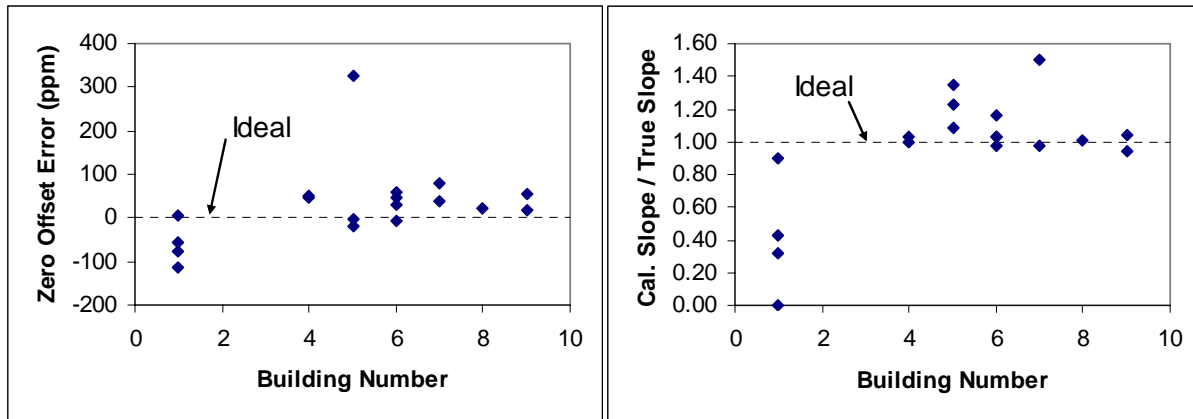


Figure 1. Zero offset errors and slopes from multipoint calibration checks of CO₂ sensors.

Single Point Calibration Checks

Table 2 and Figure 2 provide the results of the single point calibration checks of CO₂ sensors. Absolute errors ranged from – 378 to + 1013 ppm. The average and median of the absolute values of absolute error were 256 and 173 ppm, respectively. Percentage errors ranged from –100% to +258%. The average and median of the absolute values of percent error were 68% and 43%, respectively. These single point calibration checks occurred with low CO₂ concentrations, so percentage errors would likely be less at higher concentrations.

The errors were especially large in Building 2. Excluding the data from Building 2, the average and median of the absolute values of absolute error were 131 ppm and 76 ppm, respectively. Excluding the data from Building 2, the average and median of the absolute values of percent error were 31% and 18%, respectively.

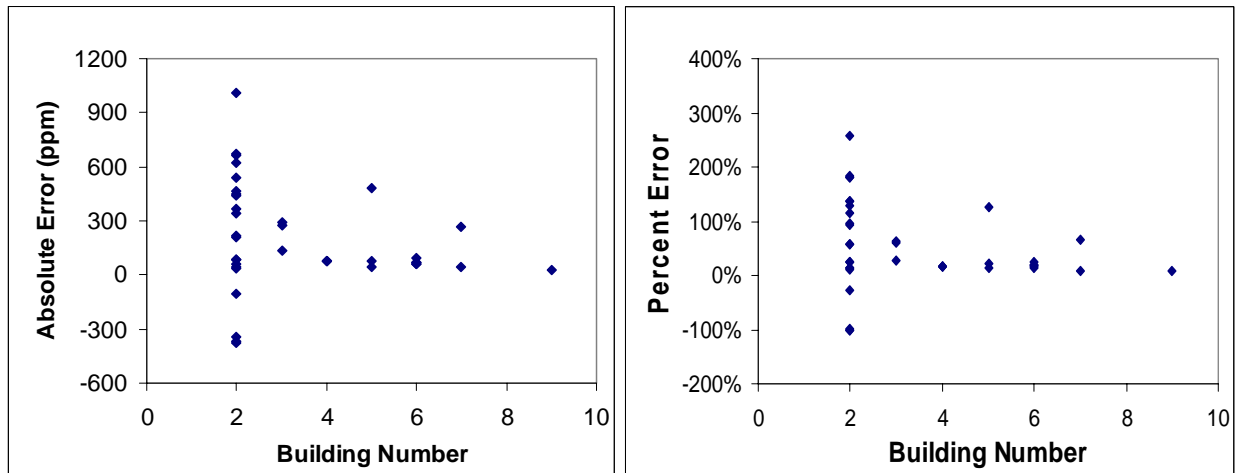


Figure 2. Absolute and percent errors from single point calibration checks of CO₂ sensors.

Comparison of Multi-point and Single point Calibration Checks

Both multipoint and single point calibration checks were completed for twelve CO₂ sensors. To evaluate the consistency of these two sensor assessment methods, we used the offset error and slope of each of the twelve multipoint calibration checks to predict the absolute error in the corresponding single point calibration check. The differences between the twelve predicted and actual measured single-point errors ranged from -35 to +20 ppm and the average of the absolute values of differences was 15 ppm. The modest magnitude of these differences is evidence of the validity of using the offset error and slope to characterize sensor accuracy.

Table 2. Results of single-point calibration checks of CO₂ sensors.

Build - ing	Sensor Code	“True” Conc. (ppm)	Absolute Error (ppm)	% Error	Reported Sensor Age (years)	Sensor Manufacturer Code
2	2a-1	394	58	15%	4	3
2	2a-2	377	38	10%	4	3
2	3a-1	369	341	92%	4	3
2	3a-2	377	48	13%	4	3
2	4a-1	395	540	137%	4	3
2	4a-2	378	-378	-100%	4	3
2	6a-2	376	215	57%	4	3
2	6a-2 repeat	375	213	57%	4	3
2	7a-2	372	-371	-100%	<4	4
2	8a-1	360	662	184%	4	3
2	8a-2	350	89	25%	4	3
2	9a-1	368	668	182%	4	3
2	9a-2	393	1013	258%	4	3
2	10a-2	377	363	96%	4	3
2	11a-2	361	-103	-29%	4	3
2	12a-1	396	452	114%	4	3
2	13a-1	342	621	182%	4	3
2	13a-2	340	437	129%	4	3
2	14a-1	342	-342	-100%	4	3
2	14a-2	340	469	138%	4	3
2	15a-1	359	85	24%	4	3
3	unit 1	462	292	63%	--	5
3	unit 2	463	276	60%	--	5
3	unit 3	487	133	27%	--	5
4	1015	457	74	16%	1	4
4	1016	459	76	17%	1	4
4	1017	472	78	17%	1	4
5	Circle	378	482	127%	5	5
5	Triangle	376	48	13%	5	5
5	Square	358	76	21%	5	5
6	Courtroom 1	381	69	18%	2	4
6	Courtroom 2	364	92	25%	2	4
6	Courtroom 3	380	71	19%	2	4
6	Courtroom 4	391	59	15%	2	4
6	Courtroom 5	423	63	15%	2	4
7	Classroom 110	413	267	65%	1	6
7	Classroom 127	466	43	9%	1	6
9	AHU 1	350	29	8%	1	6

DISCUSSION

To place the results of this study in context, one must have an estimate of the required accuracy of CO₂ sensors used in commercial buildings, e.g., for demand controlled ventilation.

While most systems only measure the indoor CO₂ concentration⁴, the difference between indoor and outdoor CO₂ concentration is a better indicator of building ventilation rate and outdoor CO₂ concentrations in urban areas vary significantly with location and time. One needs to be able to distinguish with reasonable accuracy the difference between peak indoor and outdoor CO₂ concentrations found in commercial buildings. We will assume that 20% accuracy is required for the subsequent discussion, but further research or analyses are recommended to better define the accuracy needed for effective demand controlled ventilation. 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 CO₂ concentrations at three indoor locations and one outdoor location. If one considers the maximum one-hour average differences between indoor and outdoor CO₂ concentration⁵ from this EPA study, the minimum was 55 ppm, maximum was 777 ppm, average was 310 ppm, and median was 269 ppm. If one selects a 20% accuracy in measuring the average peak indoor-outdoor CO₂ concentration difference as a minimum requirement, then 62 ppm (one fifth of 310 ppm) is a minimum expectation for CO₂ measurement accuracy in offices. Based on our predicted error at 600 ppm from the multipoint calibration checks, seven of 18 CO₂ sensors would not meet this expectation, and many fail by a very large margin.

Classroom CO₂ concentrations tend to be higher than office CO₂ concentrations, thus, one might accept larger CO₂ measurement errors in classrooms. The most representative large data set is from a survey of 201 classrooms (two thirds were modular classrooms) in California (CARB 2004). The study report does not provide peak indoor-outdoor CO₂ concentration

⁴ Some sensors use the lowest concentration measured in a period of time to automatically reset the sensor's zero reading. This automatic zeroing process assumes that CO₂ concentrations in the building are periodically as low as the outdoor CO₂ concentration and that that outdoor concentration has a specific value, e.g., 400 ppm.

⁵ Based on authors' analyses of the CO₂ data from this study.

differences, but it does report that in 43% of classrooms indoor CO₂ exceeded 1000 ppm and that a typical outdoor CO₂ concentration was 425 ppm. Thus, we can estimate that in 43% of classrooms, peak indoor CO₂ exceeded outdoor CO₂ by 575 ppm. The school-day average indoor CO₂ concentration was 1070 ppm (an estimated 645 ppm above that outdoors) but presumably this average is substantially impacted by very high CO₂ levels, above 2000 ppm, in a modest number of classrooms. Based on these data, one might select one fifth of a typical 600 ppm indoor-outdoor concentration difference, i.e., 120 ppm, as a minimum expectation for CO₂ measurement accuracy in classrooms. Based on our predicted error at 1000 ppm⁶ from the multipoint calibration checks, eight of 18 CO₂ sensors would not meet this expectation, and several fail by a large margin.

Due to the small sample size, a formal statistical analysis of the relationship between accuracy and sensor manufacturer, design features, and sensor age was not warranted. From inspection of the data, sensors from manufacturer 4 and 6 appeared to have generally smaller errors. We suspect, based on sensor specifications, that manufacturer 6 uses a sensor from manufacturer 4. The sample of dual-beam sensors was very small, thus, we were unable to determine whether dual-beam sensors had a superior performance. Based on an examination of plots, there was no clear relationship of accuracy with sensor age.

This study has important limitations that should be mentioned. Because of the small sample size, this study should be considered only a pilot study to provide an initial indication of the in-situ performance of CO₂ sensors. To obtain more representative data on CO₂ sensor accuracy, a substantially larger study from a probability sample of buildings is needed. Second, the scope of this study was very limited. The reasons for poor CO₂ sensor accuracy were

⁶ We used the predicted error at 600 ppm for offices, because peak office CO₂ concentrations tend to be near 600 ppm. We used the predicted error at 1000 ppm for classrooms, because peak classroom CO₂ concentrations tend to be near 1000 ppm.

not investigated. For example, based on the data collected, we cannot determine whether the identified accuracy problems are the consequence of technical limitations of low cost CO₂ sensors or due to failures of sensor users to maintain and calibrate sensors.

CONCLUSION

The study provides a strong indication that the accuracy of CO₂ sensors, as they are applied and maintained, in commercial buildings is frequently less than is needed to measure typical maximum values of one-hour-average indoor-outdoor CO₂ concentration differences with less than a 20% error. Thus, despite the small size of this study, we can conclude that there is a need for more accurate CO₂ sensors and/or better sensor maintenance or calibration procedures.

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