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ACCURACY OF CO_2 SENSORS IN COMMERCIAL BUILDINGS: A PILOT STUDY

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ABSTRACT

Carbon dioxide (CO_2) sensors are often deployed in commercial buildings to obtain CO_2 data that are used to automatically modulate rates of outdoor air supply. The goal is to keep ventilation rates at or above code requirements, but to also to save energy by avoiding over-ventilation relative to code requirements. However, there have been many anecdotal reports of poor CO_2 sensor performance in actual commercial building applications. This study evaluated the accuracy of 44 CO_2 sensors located in nine commercial buildings to determine if CO_2 sensor performance, in practice, is generally acceptable or problematic. CO_2 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 CO_2 sensors used in commercial buildings is frequently less than is needed to measure peak indoor-outdoor CO_2 concentration differences with less than a 20% error. Thus, we conclude that there is a need for more accurate CO_2 sensors and/or better sensor maintenance or calibration procedures.

INTRODUCTION

People produce and exhale carbon dioxide (CO_2) as a consequence of their normal metabolic processes; thus, the concentrations of CO_2 inside occupied buildings are higher than the concentrations of CO_2 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 CO_2 concentrations (ASTM 1998). For example, under steady conditions, if the indoor CO_2 concentration in an office work environment is 650 parts per million above the outdoor concentration, the ventilation rate is approximately 15 cfm per person. In many real buildings, occupancy and ventilation rates are not stable for sufficient periods to enable an accurate determination of ventilation rate from CO_2 data; however, CO_2 concentrations remain an approximate and easily measured surrogate for ventilation rate. The difference between the indoor and outdoor CO_2 concentration is also an indicator of the indoor concentrations of other occupant- generated bioeffluents, such as body odors.

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) and higher CO_2 concentrations in schools have been associated with increased student absence (Shendell et. al 2004). Shaughnessy et al (2006) found poorer student performance on standardized academic performance tests correlated with increased CO_2 in classrooms and Wargocki and Wyon (1996) found that students performed various school-work tasks less rapidly or less accurately when the classroom CO_2 concentration was higher.

In a control strategy called demand controlled ventilation, CO_2 sensors, sometimes called CO_2 transmitters, are often used in commercial buildings to obtain CO_2 data that are used to automatically modulate rates of outdoor air supply. The goal is to keep ventilation rates at or above code 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 code requirements. 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.

Reviews of the research literature on demand controlled ventilation (Apte 2006, Emmerich and Persily 2001, Fisk and de Almeida 1998) indicates a significant potential for energy savings, particularly in buildings or spaces with a high and variable occupancy. However, there have been many anecdotal reports of poor CO_2 sensor performance in actual applications of demand controlled ventilation. In a presentation by the Iowa Energy Center[1] on an intercomparison of three CO_2 sensors over time, the measured concentrations of different sensors varied by as much as 265 ppm.

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[1] John House, Iowa Energy Center, **jhouse@nrcan.gc.ca**

Based on the prior discussion, there is a good justification for monitoring indoor CO_2 concentrations and using these concentrations to modulate rates of outdoor air supply. However, this strategy will only be effective if CO_2 sensors have a reasonable accuracy in practice. The objective of this study was; therefore, to gain some initial data on the performance of CO_2 sensors in field settings to determine if CO_2 sensor performance, in practice, is generally acceptable or problematic.

METHODS

Two different protocols were employed to assess the accuracy of 44 CO_2 sensors located in 9 buildings within California. When possible, we used bags of CO_2 calibration gases to evaluate sensor performance at five CO_2 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 CO_2 sensors located in buildings sampled each of the calibration gases. The CO_2 concentrations reported on the computer screen of the building's data acquisition system or on the CO_2 sensor display were recorded[2]. The data obtained were processed to obtain an offset error and slope or sensor gain error using a least-squares linear regression of measured CO_2 concentration verses "true" CO_2 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 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 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 CO_2 sensors using a co-located and calibrated reference instrument. The protocol was very simple. A research grade CO_2 instrument was calibrated, taken to the building, and 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 were recorded manually. The data were 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. We also calculated a percentage error equal to the absolute error divided by the true CO_2 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 CO_2 concentrations of 470 ppm or less.

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[2] In three buildings, the CO_2 concentrations on the CO_2 sensor's display were used, but in all cases we confirmed that the building's data acquisition system reported the same CO_2 concentration as the sensor display.

The reference instrument used for the single point calibrations was the EGM-4 model from PP Systems, Amesbury, MA. The instrument 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 ± 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 slope 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, the calibrated EGM-4 was intercompared with another research grade, but less accurate, CO_2 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 EGM-4 analyzer to measure the CO_2 concentrations in two cylinders of CO_2 calibration gas that were not employed in the EGM’s calibration. In these two measurements, the EGM reported a CO_2 concentration approximately 30 ppm less than indicated on the calibration gas cylinders. Altogether, these tests imply that the uncertainty in our reference CO_2 measurements was about ±30 ppm.

All of the 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 manfacturers’ accuracy specifications ranged from ±40 ppm ±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 CO_2 sensor. The buildings were used for healthcare, education, software industry, judicial, and state office applications. There were six brands of CO_2 sensors[3] 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 CO_2 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 CO_2 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 CO_2 concentration measurement errors at true CO_2 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

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[3] Some manufacturers do not make theier own sensors, they market sensors from other manufacturers.

accuracy of sensors of the same brand was highly variable. There was 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 CO_2 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 Manu-facturer 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: R^2 is the square of the Pearson correlation coefficient

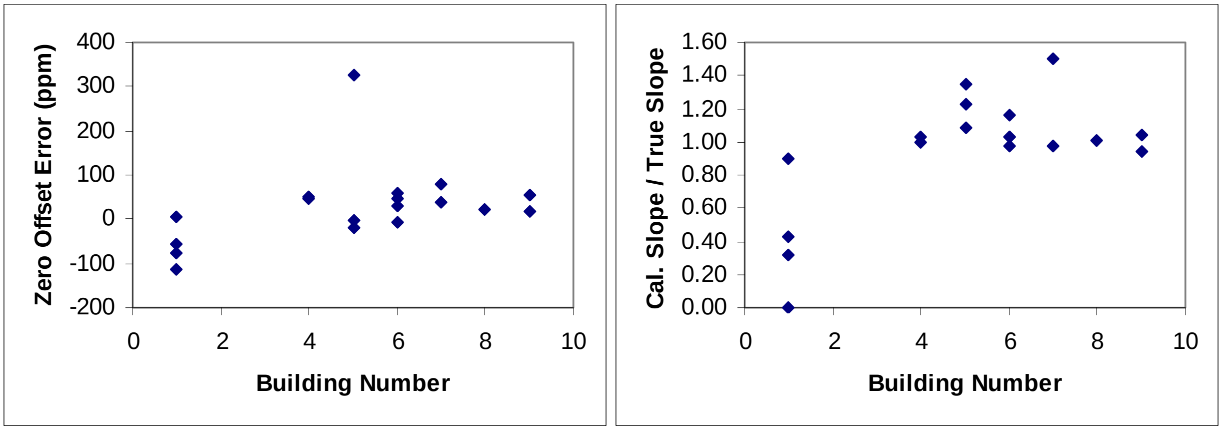

Figure 1. Zero offset errors and slopes from multipoint calibration checks of CO_2 sensors.

Single Point Calibration Checks

Table 2 and Figure 2 provide the results of the single point calibration checks of CO_2 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 CO_2 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.

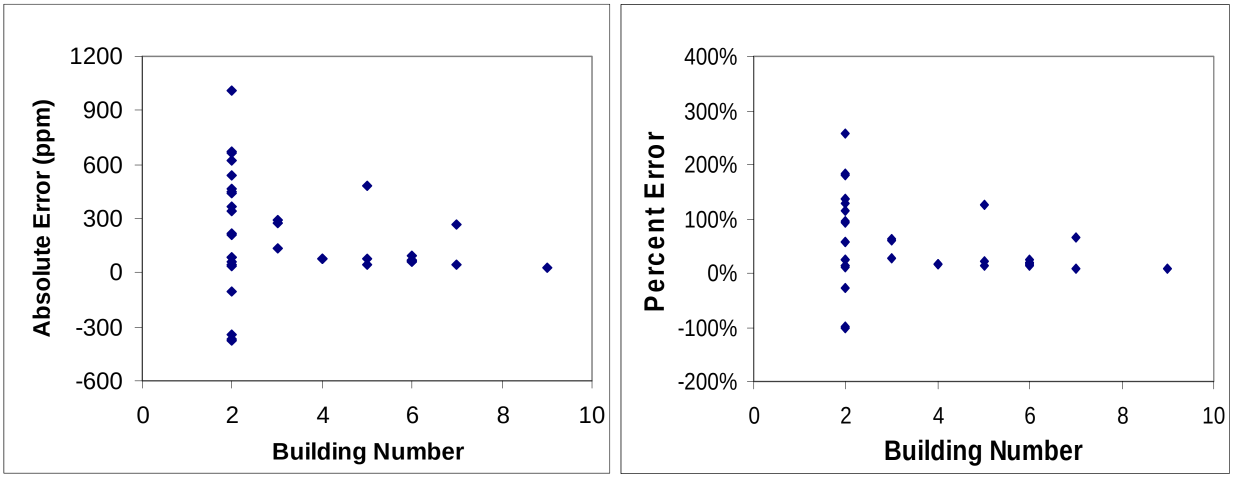

Figure 2. Absolute and percent errors from single point calibration checks of CO_2 sensors.

Comparison of multi-point and single point calibration checks

Both multipoint and single point calibration checks were completed for twelve CO_2 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 CO_2 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	7
7	Classroom 127	466	43	9%	1	7
9	AHU 1	350	29	8%	1	7

DISCUSSION

To place the results of this study in context, one must have an estimate of the required accuracy of CO_2 sensors used in commercial buildings, e.g., for demand controlled ventilation. While most systems only measure the indoor CO_2 concentration[4], the difference between indoor and outdoor CO_2 concentration is a better indicator of building ventilation rate and outdoor CO_2 concentrations in urban areas vary significantly. One needs to be able to distinguish with reasonable, e.g., 20%, 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 selects a 20% accuracy in measuring the average peak indoor-outdoor CO_2 concentration difference as a minimum requirement, then 62 ppm (one fifth of 310 ppm) is a minimum expectation for CO_2 measurement accuracy in offices. Based on our predicted error at 600 ppm from the multipoint calibration checks, seven of 18 CO_2 sensors would not meet this expectation, and many fail by a very large margin.

Classroom CO_2 concentrations tend to be higher than office CO_2 concentrations, thus, one might accept larger CO_2 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 CO_2 concentration differences, but it does report that in 43% of classrooms indoor CO_2 exceeded 1000 ppm and that a typical outdoor CO_2 concentration was 425 ppm. Thus, we can estimate that in 43% of classrooms, peak indoor CO_2 exceeded outdoor CO_2 by 575 ppm. The school-day average indoor CO_2 concentration was 1070 ppm (an estimated 645 ppm above that outdoors) but presumably this average is substantially impacted by very high CO_2 levels, above 2000 pm, 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 CO_2 measurement accuracy in classrooms. Based on our predicted error at 1000 ppm[6] from the multipoint calibration checks, eight of 18 CO_2 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. 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 CO_2 sensors. To obtain more representative data on CO_2 sensor accuracy, a

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[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 CO_2 concentrations in the building are periodically as low as the outdoor CO_2 concentration and that that outdoor concentration has a specific value, e.g., 400 ppm.

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

[6] We used the predicted error at 600 ppm for offices, because peak office CO_2 concentrations tend to be near 600 ppm. We used the predicted error at 1000 ppm for classrooms, because peak classroom CO_2 concentrations tend to be near 1000 ppm.

substantially larger study from a probability sample of buildings is needed. Second, the scope of this study scope was very limited. The reasons for poor CO_2 sensor accuracy were 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 CO_2 sensors or due to failures of sensor users to maintain and calibrate sensors.

CONCLUSION

The study provides a strong indication that the accuracy of CO_2 sensors used in commercial buildings is frequently less than is needed to measure peak indoor-outdoor CO_2 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 CO_2 sensors and/or better sensor maintenance or calibration procedures.

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