PROF. STUART BATTERMAN (Orcid ID : 0000-0001-9894-5325)

Article type : Original Article

Ventilation Rates in Recently Constructed US School Classrooms

Stuart Batterman[1,*], Feng-Chiao Su[1], Andrew Wald[1], Floyd Watkins[1], Christopher Godwin[1], Geoffrey Thun[1]

[1] University of Michigan, Ann Arbor, MI, USA

[*]Corresponding email: stuartb@umich.edu

Aug. 26, 2016

joefcsu@umich.edu, ajwald@umich.edu, fwatkins@umich.edu, ccgodwin@umich.edu, gthun@umich.edu

Summary

Low ventilation rates (VRs) in schools have been associated with absenteeism, poorer academic performance, and teacher dissatisfaction. We measured VRs in 37 recently constructed or renovated and mechanically-ventilated U.S. schools, including LEED and EnergyStar-certified buildings, using CO_2 and the steady-state, build-up, decay and transient mass balance methods. The transient mass balance method better matched conditions (specifically, changes in occupancy) and minimized biases seen in the other methods. During the school day, air change rates (ACRs) averaged 2.0 ± 1.3 h^{-1}, and only 22% of classrooms met recommended minimum ventilation rates. HVAC systems were shut off at the school day close, and ACRs dropped to 0.21 ± 0.19 h^{-1}. VRs did not differ by building type, although cost-cutting and comfort measures resulted in low VRs and potentially impaired IAQ. VRs were lower in schools that used unit ventilators or radiant heating, in smaller schools and larger classrooms. The steady-state, build-up and decay methods had significant limitations and biases, showing the need to confirm that these methods are appropriate. Findings highlight the need to increase VRs and to ensure that energy saving and comfort measures do not compromise ventilation and IAQ.

Keywords

Ventilation, air change, carbon dioxide (CO_2), high performance buildings

Practical Implications

Occupancy patterns in school classrooms were dynamic, and VRs derived using methods that account for changes in occupancy over the school day were most applicable. In nearly all classrooms, VRs were below the minimum recommended guidelines. VRs depended on the HVAC type and operation, but not whether the building was designated as a conventional or “high performance.” Lower VRs were found in classrooms using unit ventilators, radiant heating systems, and sometimes energy recovery units, and in smaller buildings and larger classrooms. Air change rates fell to very low levels in the evening and early morning when HVAC systems were shut off. Additional ventilation, better design and operation, and education regarding ventilation is needed.

1 Introduction

The importance of ventilation has long been recognized as a determinant of comfort, health, productivity and overall indoor environmental quality (IEQ) [1]. While critical for assessing and interpreting IEQ, relatively few studies have adequately measured ventilation rates (VRs) or otherwise characterized the ventilation design of study buildings [2]. In school buildings, low VRs have been associated with higher rates of absenteeism, poorer performance on academic tests, and teacher dissatisfaction [3-11]. The school environment is particularly important given that children represent a vulnerable and susceptible population. Beyond ventilation issues, IEQ problems in schools include water damage, chipping paint, odors and inadequate, deferred, and outsourced maintenance [12]. Given concerns of energy consumption and, to a lesser extent, IEQ, a number of school districts have begun to construct new schools and renovate old schools that meet energy and environmental targets, such as the US Green Building Council’s Leadership in Energy & Environmental Design (LEED) standards [13]. In addition to saving energy, "high performance" buildings may improve learning ability and test scores, contribute to staff retention and employee satisfaction, reduce distraction and enhance learning. However, the current understanding of the linkage between ventilation and school health is incomplete [11, 14, 15]. Many studies have reported CO_2 concentrations [4, 8, 16-23], a simple indicator related to crowding and ventilation for which upper limits from 1000 to 1500 ppm have been suggested [16, 17, 24]. While less frequently reported, VRs should meet minimum targets specified in codes and standards [17]. More broadly, research is needed that identifies building design and operational elements that most directly affect the health, learning and productivity of students and staff.

This paper reports on CO_2 levels and VRs measured in the *Environmental Quality and Learning in Schools* (EQUALS) study, which is investigating IEQ in conventional and high performance (i.e., LEED- and EnergyStar-certified) buildings. The selected schools were constructed or renovated within the last 15 years, and the sample was balanced between LEED, EnergyStar (ES) and conventional buildings. While school environments are receiving increased attention, this study is innovative in comparing VRs in conventional and high performance buildings, comparing several methods for estimating VRs, and exploring factors that might explain the variation of the results.

2 Methods

2.1 School selection and recruitment

Schools eligible for the study were constructed or renovated within the past 15 years, served elementary age children, and had multiple classrooms at each grade level. In addition, we desired comparable numbers of high performance buildings and conventional buildings, buildings clustered within school districts, and kept distances within a day's drive of our Ann Arbor/Detroit team (primarily for logistical reasons, although proximity also helped ensure a similar climate). Schools were identified from the U.S. Green Building Council's LEED Projects Directory [25] and the US EPA's ES database [26]. Conventional buildings were found by examining large or growing school districts in the study region. District and school websites, news reports on school openings and bond issues, and historical aerial photographs on Google Earth Pro were searched to investigate construction histories.

Recruitment materials that described study objectives and methods were emailed to school district administrators. Priority was given to districts with at least two schools meeting selection criteria. Follow-up phone calls and emails explained study details, confirmed the number of schools matching our criteria that were able to participate, secured district-level approvals, and obtained permission to contact school principals (heads). Schools and districts were promised anonymity. Each participating school district completed a letter of agreement that named the participating schools and identified an individual to receive study results on behalf of the district. After receiving permissions, typically with an official introduction by the district-level contact, we began a rolling coordination of field visits with school administrators. Using emails and phone calls, we introduced the study to school administrators, obtained endorsements from the principal and building services director, determined dates and times for school visits, identified four classrooms per school for inspection and monitoring, requested teacher email lists for an online survey, and confirmed other study details. Classrooms were selected by the school's principal and typically were dispersed throughout the school. All study elements complied with our Institutional Review Board, including informed consent of the teachers participating in the survey.

Field work was conducted from October 2015 to April 2016. One to three schools were scheduled per week during regular school days. In the same week, we visited schools in the same district, thus simplifying coordination and scheduling. Schools were visited for two or three days. Typically, the team would arrive early Tuesday morning, deploy indoor and outdoor sampling equipment, conduct walkthrough and other assessments (described next), and retrieve equipment late Wednesday afternoon. Snowfalls closed four schools (designated as S19, S21, S29 and S30) for a portion of the scheduled sampling period; in cases, sampling was extended to a third day.

2.2 Walkthrough inspections, IEQ measurements, occupancy log

In each school, walkthrough inspections were completed in four classrooms, common areas (e.g., gymnasiums, cafeterias and hallways), mechanical areas, and adjacent outdoor areas. School and classroom sizes and volumes were measured. Information regarding the design, operation and maintenance of the building and ventilation system was obtained by visual inspection and via engineering documents. When possible, we visually inspected HVAC system filters and classified classrooms as being served by clean (n=107, 73%), dirty (n=15, 10%) or very dirty filters (n=25, 17%). Teachers were asked to complete an occupancy survey that indicated the number of students and adults present throughout the school day.

Instrumentation to monitor IEQ was deployed in the four classrooms simultaneously during at least two regular (occupied) school days. Similar instrumentation was placed on the school grounds or the building roof. CO_2 concentrations were measured using infrared sensors (C7632A, Honeywell Corp., Morristown, NJ) calibrated with zero air and a certified CO_2 gas (1,011 ppm, Scott Specialty Gases, Plumstead, PA). CO_2 levels, temperature and relative humidity were recorded continuously using miniature loggers (H08 and U10, Onset Computer Corporation, Bourne, MA). Sensors were calibrated quarterly. The average absolute drift was <4% for a 1000 ppm reading; only one unit exceeded a 10% change. CO_2 levels exceeded the instrument range (2500 ppm) for at least several hours in 5 ES and 2 LEED buildings, typically in several classrooms in each building (S03C2, S11C1, S11C3, S11C4, S12C1, S12C4, S13C1, S13C4, S23C1, S23C2, S23C4, S24C1, S24C2, S24C3, S24C4, S30C2, S30C3). (ACRs for these periods were estimated using the transient mass balance simulations with the valid data subset, as described below.)

Three schools were selected for an in-depth analysis of CO_2 levels, occupancy trends, building and HVAC features that together influence VRs. These buildings, which have different types of ventilation systems, do not typify the buildings within a category. The first school (S14) is a conventional 2-story building (7395 m^2, 22 classrooms). Classrooms feature large (partially openable) windows on two walls, 1st floor classrooms have openable outside doors, and each classroom has a vertical unit ventilator (UV; maximum rated flow of 755 L s^{-1}, minimum outside air (OA) of 151 L s^{-1}). Other areas are served by small central air handling units (AHUs). Heat is also supplied by baseboard radiators. Two teachers disabled the UV in their classrooms: in room 104 for noise and comfort reasons; and in room 107 for odor reasons, but the outside door was left open for ventilation, weather permitting. The second school (S22) is a smaller (4970 m^2, 22 classrooms) LEED (silver) certified building. This is the only building studied that used dedicated outdoor air systems (DOASs). One DOAS, equipped with an enthalpy wheel and geothermal heating coil, provides conditioned and 100% OA to each classroom (nominally 179 L s^{-1}). A second DOAS supplies non-classroom areas. Each classroom has a geothermal heat pump to meet temperature needs using recirculated classroom air (nominally 354 L s^{-1}). Return air is recycled through the heat pump or ducted back to the DOAS energy recovery unit (ERU). The third school (S12) is a medium-sized ES building (5388 m^2, 25 classrooms). Three AHUs with ERUs service the building. AHU1 covers most classrooms; AHU2 covers first floor offices, the library and the remaining classrooms; and AHU3 services the gym, cafeteria and kitchen. AHU1 and 2 are dual-duct variable air volume (VAV) systems with terminal boxes at each classroom. On inspection, these systems appeared to be operating in bypass mode (the ERU wheel was inactive, OA dampers were closed, and sensors reported that AHU1 and 2 were drawing only 378 and 590 L s^{-1} of OA, respectively. These schools are further described in the supplemental information (SI).

2.3 Determination of ventilation rates

VRs were determined in each classroom using CO_2 as a tracer gas, classroom-specific parameters (volume, grade-level and occupancy) and four methods detailed elsewhere [27]. The first used the "steady-state" method [28-30], the maximum CO_2 concentration (assumed to be the steady-state level) over the school day, the room volume, and the CO_2 generation rate for the 2 h prior to the CO_2 peak. For children, grade level-specific generation rates were based on the Dubois equation [28], height and weight data from U.S. representative growth charts, and an activity level of 1.4 MET. These rates ranged from 0.147 L min^{-1} $person^{-1}$ for pre-kindergarten children to 0.264 L min^{-1} $person^{-1}$ for 6th graders. For adults, the CO_2 generation rate (0.442 L min^{-1} $persion^{-1}$) was based on height and weight data for women of age 20 to 70 years from NHANES 1999-2006 and an activity level of 1.7 MET, appropriate for a teacher walking about the classroom. The second VR method used the "decay" ("step-down") method [28, 29] that fitted the exponential-like decrease in CO_2 concentrations after the classroom was emptied. The third method determined ACRs in the morning using the "build-up" or "step-up" method [31] and a nominal period from 08:00 to 12:00. Actual start and stop times were allowed to vary by ± 1 h so as to maximize the concentration change over the period. The steady-state concentration required by this method was determined using both the midpoint method [31] and an implicit method that numerically solves the build-up and steady-state equations simultaneously [27]. The implicit method improves stability and better addresses variable occupancy and non-ideal shapes of the CO_2 build-up curve. Fourth, a transient mass balance (simulation) method was used for both occupied and unoccupied periods that fitted the VR by minimizing the sum of squares between observed and simulated CO_2 concentrations. This method used 15 min averages for CO_2 measurements and CO_2 generation rates (derived from teacher-reported occupancy data), a generalized reduced gradient solver, and a numerically efficient formulation based on a fully-mixed mass balance model. In addition to the VR, the replacement air concentration (C_R) and the children's metabolic level (MET) were fitted within constraints (350 ppm < C_R < 450 ppm, and 1.2 < MET < 1.6). The sensitivity of results to key parameters was determined for each method.

VRs were determined for four occupied periods: two complete school days (08:00 to 15:00) and two mornings (08:00 to 12:00); and for two unoccupied periods: evenings (18:00 to 24:00) and early morning (24:00 to 06:00). Sometimes slightly different times were used given the logistics of sampler deployment and retrieval, or if CO_2 levels went off-scale. Estimates used 15-min average concentrations and 400 ppm as the nominal outdoor CO_2 concentration (confirmed by outdoor measurements).

2.3.1 Data analysis

All hand written and teacher survey data were double-entered and confirmed. Teacher-reported occupancy data were reduced to 15-min averages. At least 4 h of valid data in each period were required to compute VRs. For the transient mass balance method, a minimum model fit ($R^2 \geq 0.25$) was required (most values were much higher). CO_2 trends in each classroom were plotted, inspected to identify possible anomalies, and periods with CO_2 levels exceeding sensor ranges were excluded. The outdoor air flow rate per person (V_0, L s^{-1} $person^{-1}$) was calculated for occupied periods (separately for steady-state, build-up and transient mass balance methods) using both the average and maximum occupancy in the classroom.

Descriptive and statistical analyses were computed after averaging the VR and V_0 data for the same classroom measured on different days. Possible differences in school characteristics by school type were examined using Chi-square tests for categorical variables and Kruskal–Wallis (KW) tests for continuous variables. Differences in CO_2 levels and ACRs by school type and other variables were tested using ANOVA and KW tests. The between- and within-school variance was apportioned using random effects models and balanced samples, and tested using F tests. The fraction of classrooms that exceeded current minimum VR recommendation for classrooms (7.1 L s^{-1} $person^{-1}$ using default occupancy and floor areas [17]) was determined. These analyses were performed using SAS, Excel and R.

3 Results

3.1 School and classroom characteristics

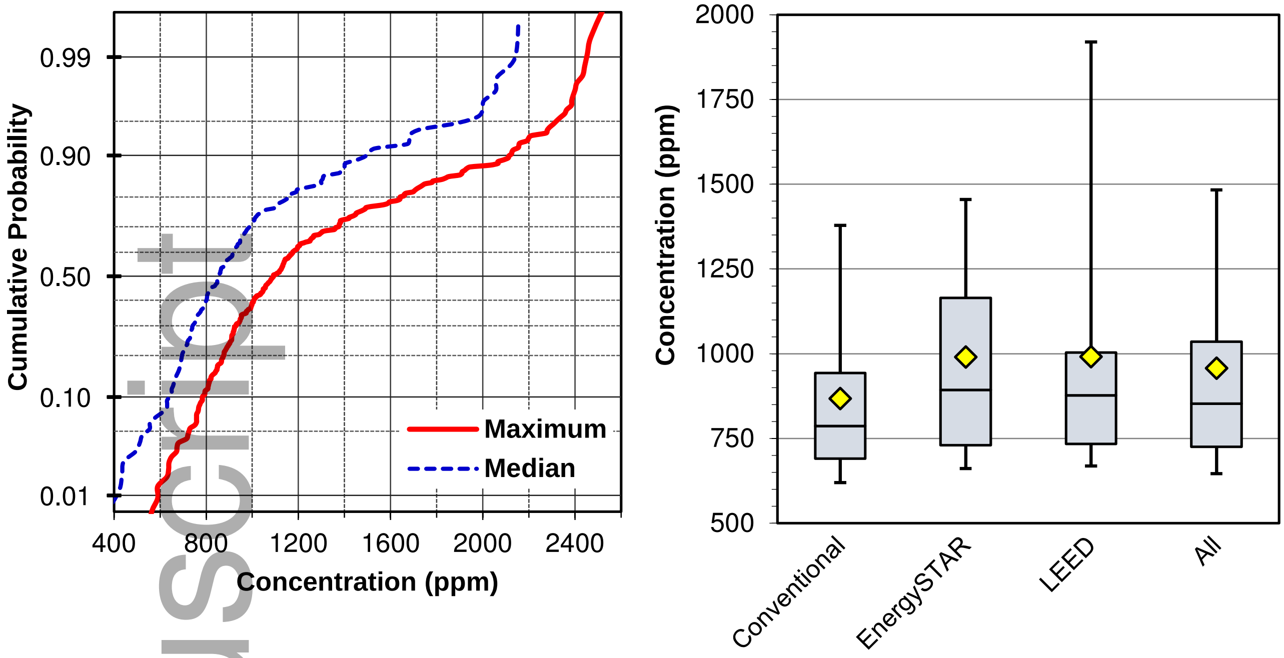
The 37 schools included both suburban and urban school districts in southern Michigan, northern Indiana, northern and southeastern Ohio, and eastern Illinois. The sample included 10 conventional, 15 ES and 12 LEED buildings. Three buildings designed but not certified to LEED criteria were placed in the LEED group (S24, S33, S34). Most buildings were new construction, however, ten were full renovations of older structures. The typology and other aspects of the schools varied considerably, e.g., configurations included bars, groups, wings, courtyards and pods. The sample included 21 multistory buildings and 16 single-story slab-on-grade construction. No portable classrooms were studied. All buildings used mechanical ventilation, 13 relied on central AHUs, four relied solely on classroom UVs, and two used an AHU and UV mix. One school (S22) used a central dedicated outside air system (DOAS) and individual UVs to heat and cool individual classrooms. Nearly all classrooms (94%) had exterior walls and windows, and a subset had doors to the outside (24%) or an adjoining restroom (36%). Teachers were able to open windows in most classrooms (65%), although few teachers reported opening windows. Under 10% of the classrooms had heaters, fans or window air conditioners. Characteristics of the buildings and classrooms are described in the SI.

A few school characteristics differed by building type. The average size of conventional schools (8860 m^2) was larger the LEED (7463 m^2) and ES (6766 m^2) schools, and the average area of classrooms in LEED schools (87 m^2) was smaller than those in conventional (94 m^2) and ES (96 m^2) schools. ES and LEED schools were more likely to be in agricultural areas and near highways. Most ES schools used a wing typology, while conventional and LEED schools predominantly used bar and grouped forms.

3.2 CO_2 concentrations

Distributions of the school day median and maximum 15-min CO_2 concentrations among the 147 classrooms are shown in Figure 1. The median CO_2 level during the school day exceeded 1000 ppm in 28% of classrooms, 1500 ppm in 9%, and 2000 ppm in 4% of classrooms. Peak (15-min average) concentrations exceeded 1400 ppm in 36% of the classrooms and 2000 ppm in 19%. Median CO_2 levels in ES and LEED schools were higher, but not significantly, than those in conventional schools. Maximum CO_2 levels differed significantly, and LEED schools had the highest levels (ANOVA and KW p-values= 0.012 and 0.027, respectively). CO_2 measurements will be affected by the number of students, classroom size and other factors, and in most cases do not represent steady-state levels.

Figure 1. Left: Probability plot showing distribution of maximum and median CO_2 concentrations across classrooms. Right: Box plots of median concentrations by building type. From 15-min CO_2 data for the occupied portion of two school days. Box plots show 10th, 25th, 50th, 75th and 90th percentiles; diamond indicates the mean.



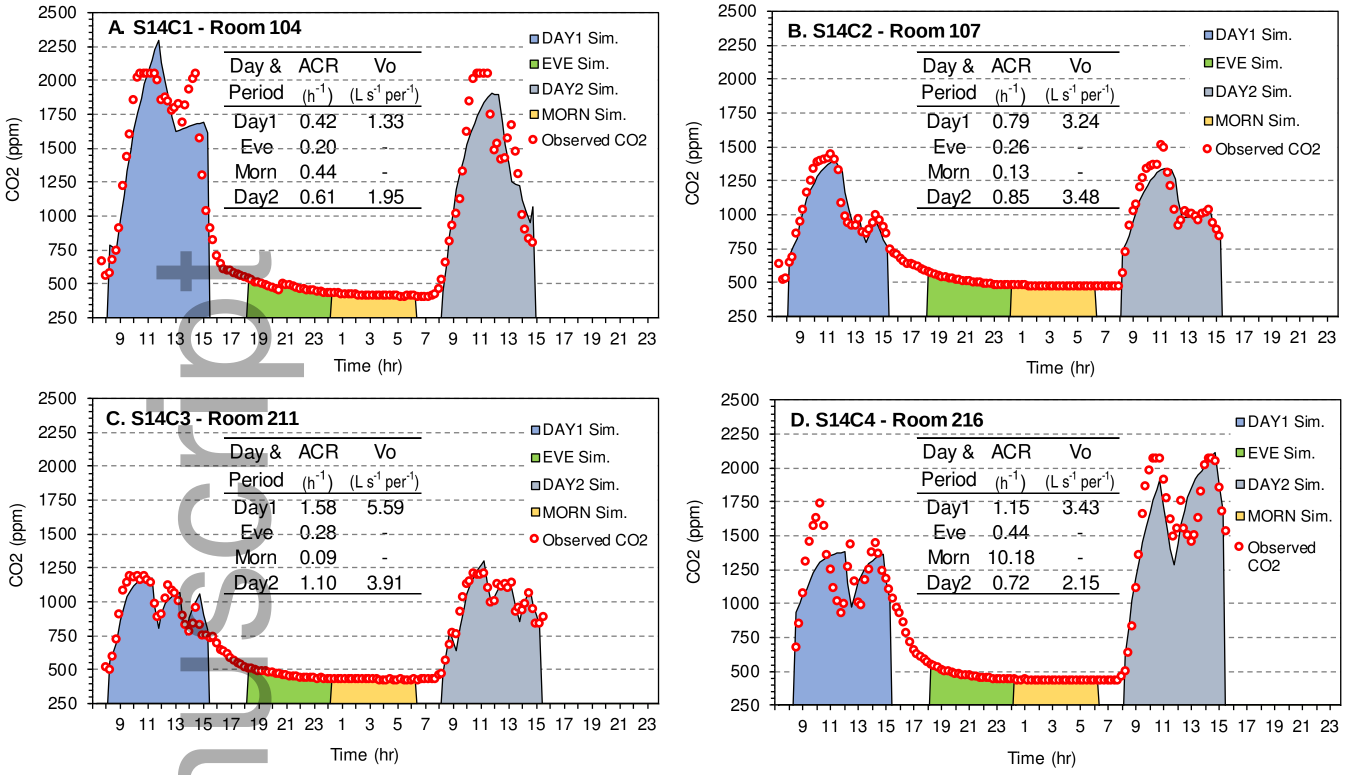
Two buildings in the same school complex had the highest CO_2 concentrations (medians from 2001 to 2156 ppm in classrooms in school S23, and 1505 to 2056 ppm in S24). CO_2 levels exceeded the sensor range by about 11:00 each morning in S23, and slightly later in S24. These small schools share similar designs. S23 is a gold-level LEED-certified building with 10 classrooms and 240 students, a single double-loaded corridor, a large open central common space, and high clerestory windows that can be opened for cross ventilation during the warmer months. A geothermal heating and cooling system supplies radiant floors and water-to-air heat pumps in each classroom, and two small (944 L s^{-1}) ERUs use 100% OA and desiccant wheels to supply the ceiling plenum. Based on 25 persons in each classroom and the rated airflow, the mechanical system provides 7.6 L s^{-1} $person^{-1}$. Based on CO_2 and transient mass balance method, the VR across the four classrooms averaged (± standard deviation) 1.9 ± 0.2 L s^{-1} $person^{-1}$, among the lowest in the sample, possibly due to clogged desiccant wheels or filters, duct leaks, or other failures. In school S24, which was slightly smaller (8 classrooms, 158 grade 5-8 students) and designed (but not certified) to the silver LEED level, VRs averaged 2.3 ± 0.8 L s^{-1} $person^{-1}$. These buildings had among the lowest VRs in the study.

The variation of median and maximum CO_2 measurements mostly resulted from school-to-school variation (72% of the total variance of the maxima) as compared to room-to-room variation within a school (28%). The modest within-school variation is unsurprising since many HVAC design and operational factors are shared across classrooms in a school. This can apply even to schools using UVs (S02, S03, S14, S17, S18, S21, S30) where greater differences in CO_2 levels may result since air between classrooms is not shared and systems may operate independently, however, this may be offset since classrooms within a school often have similar sizes, occupancy patterns, ventilation equipment and other commonalities. The examples below illustrate the diverse situations found within and across schools.

3.3 Examples of conventional, LEED and EnergyStar buildings

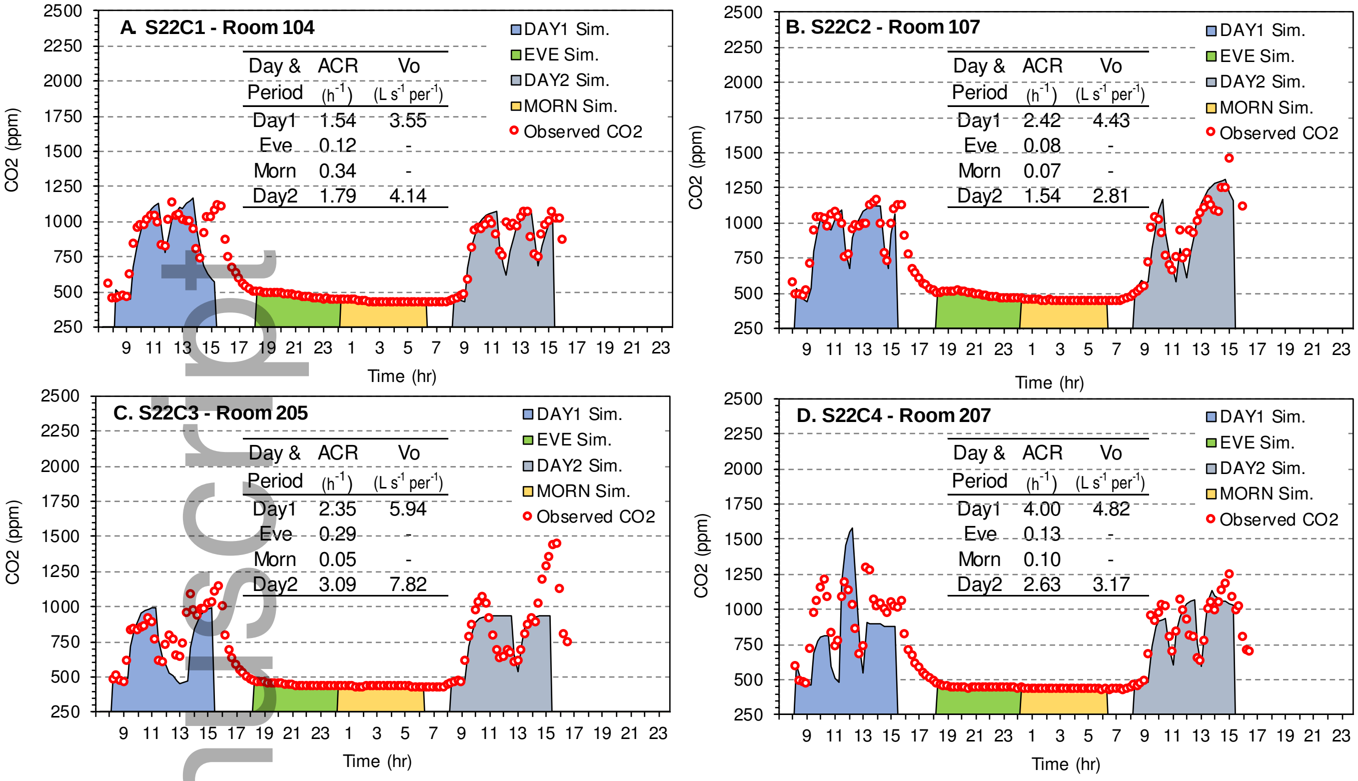
Figure 2 shows CO_2 trends monitored simultaneously in four classrooms of a conventional school building (S14). The PK-K classrooms (rooms 104 and 107) showed similar trends, but different CO_2 levels; in both rooms, teachers had disabled the UVs, but the outside door in room 107 was left open. The grade 1-3 classrooms (rooms 211 and 216) also showed large differences. CO_2 levels were correlated to VRs (figure inset), and days and classrooms with V_0 below 2.2 L s^{-1} $person^{-1}$ (rooms 104 and 216, day 2 only) had the higher CO_2 concentrations. At the end of the school day, HVAC systems were shut off and VRs fell to very low levels in evening (18:00 – 24:00) and early morning (24:00 – 06:00) periods. Simulated and observed CO_2 concentrations matched closely. VRs varied over a 3-fold range in these classrooms and were particularly low in room 104 (UV disabled, no opened doors or windows) showing the influence of occupant behavior. Results for other classrooms in this building were in the middle range across the 37 schools.

Figure 2. Observed and simulated CO_2 concentration trends in four classrooms in a conventional school (S14). Inset tables shows ACRs determined using transient mass balance method and teacher-reported occupancy for four periods, and personal V_0 for days 1 and 2, based on maximum occupancy. Observed (red circles) and simulated data (colored areas) are 15-min averages. Monitored Dec. 15-16, 2015.



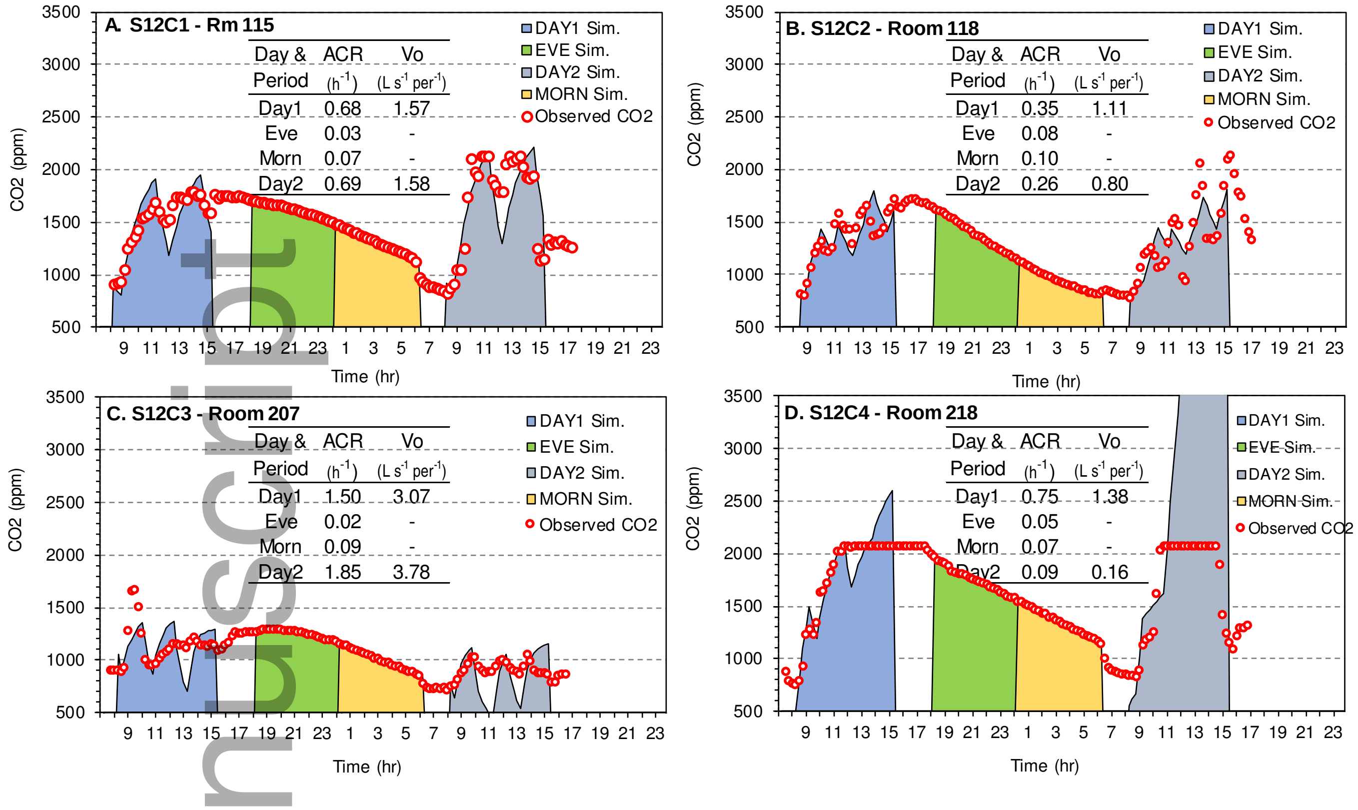
In LEED-certified building S22, CO_2 levels in classrooms fluctuated considerably over the day, but remained below 1500 ppm and generally below 1250 ppm (Figure 3). Simulated CO_2 levels fitted most measurements with exceptions of room 207 on day 1 when levels did not match a spike in simulated levels due to a brief increase in the reported occupancy (35 students for 15 min after lunch), and room 205 on late afternoon of day 2 (no change in occupancy was reported). Based on room volume and rated DOAS airflow, the ACR was 3.4 h^{-1}. Based on the transient mass balance method, ACRs across the four classrooms and two days averaged 2.4 ± 0.8 h^{-1}. The lower value obtained using CO_2 methods is not surprising since full mixing is assumed and the rated DOAS air flow may be optimistic. Still, these classrooms had some of the higher and more uniform VRs in the sample (V_0 averaged 4.6 ± 1.6 L s^{-1} person^{-1}). While additional applications should be examined, the DOAS in this school provided higher and more consistent ventilation than in most of the other schools evaluated.

Figure 3. CO_2 trends in four classrooms in a LEED-certified building (S22). Monitored Jan 21-22, 2016. Otherwise as Figure 2.



Classrooms in school S12, the ES building, had some of the higher CO_2 levels (above 2000 ppm in three of four classrooms) and lower VRs (average of 1.7 ±1.2 L s^{-1} $person^{-1}$ and only 1.1 ±0.5 L s^{-1} $person^{-1}$ excluding room 207 on a separate AHU) in the study (Figure 4). In room 218, CO_2 levels exceeded the sensor range, and ACRs were derived by fitting the morning period only. This procedure yields very high peak levels of CO_2 (2600 and 6000 ppm on days 1 and 2, respectively). The three classrooms served by AHU1 (rooms 115, 118 and 218) showed similar trends and levels of CO_2, as well as low VRs. In contrast, room 207, on separate AHU2 that primarily serviced low occupancy spaces, had much lower CO_2 levels and higher VRs. In this school, day time CO_2 levels were sufficiently high and VRs sufficiently low that CO_2 levels at the start of the following day remained above 800 ppm, well above outdoor levels.

Figure 4. CO_2 trends in four classrooms in an EnergyStar school (S12). In room 207, day 2 simulations did not achieve the minimum R^2 required (0.25). In room 218, CO_2 levels exceeded instrument range, and ACRs and V_0 are estimated for Day 1 using the 08:00 to 11:00 period and for Day 2 using the 08:00 to 10:15 period. CO_2 scale is expanded. Monitored Dec. 8-9, 2015. Otherwise as Figure 2.



3.4 ACRs during occupied periods

The three buildings and 12 classroom discussed in the previous section demonstrate many differences with respect to VRs, building and HVAC elements, operating practices and occupancy patterns. Occupancy in the classrooms was highly dynamic, e.g., teachers typically arrived before students, students and teachers left for lunch, and both small and large changes in the numbers of students (and sometimes adults) occurred throughout the school day. Nevertheless, Figures 2 to 4 demonstrate the fit that can be achieved between observed and predicted CO_2 levels, e.g., R^2 exceeded 0.80 in most classrooms. Discrepancies seemed to result from incorrect occupancy information, e.g., the timing reported by teachers was offset (Figure 2B), brief occupancy spikes that were not recorded (Figure 3D), or patterns not recalled accurately (Figure 4C). Other issues include small changes in CO_2 levels during the unoccupied early morning period, which increased the uncertainty of the VR estimates, and high CO_2 levels that exceed the sensor range.

ACRs in classrooms across the 37 schools are summarized in Table 2. Means and medians for the transient mass balance method did not show statistically significant differences by school type (conventional, ES or LEED), whether a school was new or newly renovated, whether HVAC filters were clean or dirty, whether the building was 1 or 2 stories in height, or by building floor area per student. ACRs averaged 1.5 ±1.5 h^{-1} for classrooms in the six schools using UVs (three conventional and three ES), were significantly lower compared to those served by central AHUs (2.0 ±1.3 h^{-1};

p=0.01). Smaller schools (using area, number of classrooms, or student enrollment) also had lower ACRs (medians by school size tertiles were 1.3, 1.7 and 2.0 h^{-1}, KW p=0.02; means did not vary). The 14 schools with ERUs had slightly but not statistically lower ACRs (median of 1.5 h^{-1}) than those without (1.9 h^{-1}, KW p=0.19). Finally, the larger classrooms (by area) had lower ACRs (medians of 1.9, 2.0 and 1.3 h^{-1} for volume tertiles divided by 238 and 267 m^3, respectively; KW $p \leq 0.001$; means also varied, p=0.003).

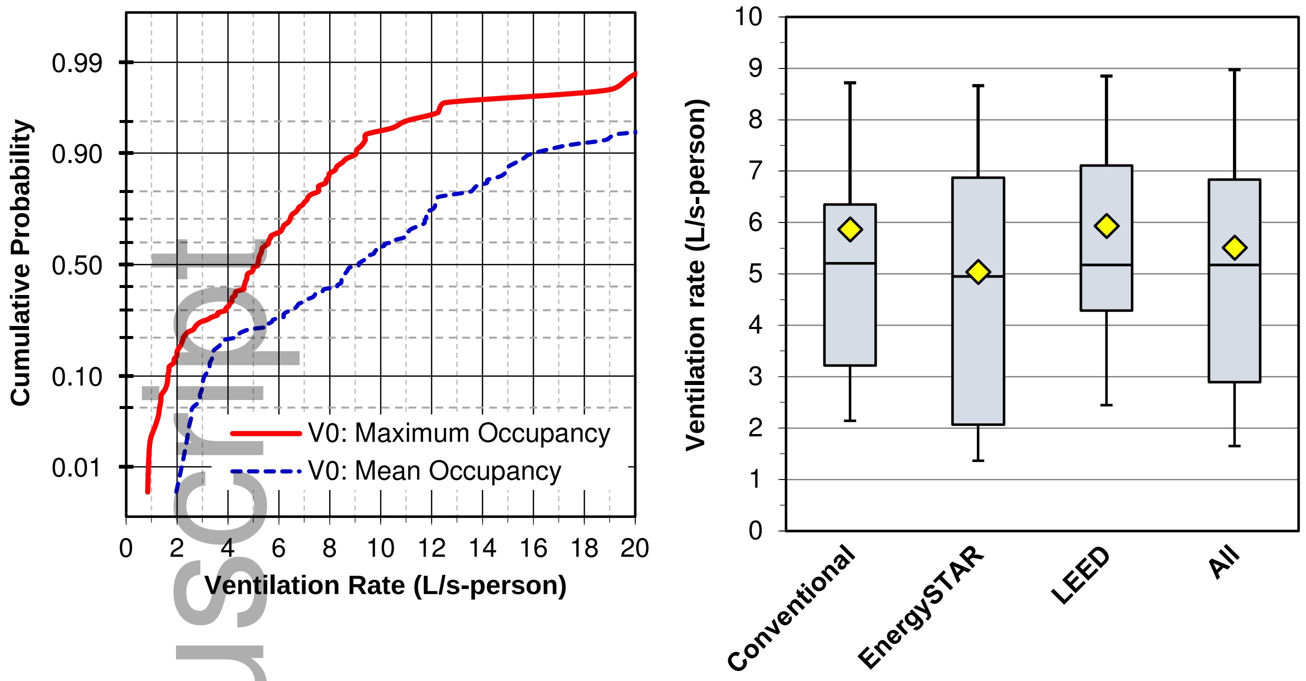
Ventilation rates per person, V_0, depended on the method and the occupancy assumption. Table 1 summarizes results and Figure 5 shows distributions and comparisons among building types. For comparison to ventilation guidelines, the maximum occupancy is most relevant; this gives a lower (more conservative) estimate of V_0, and the steady-state, build-up, and transient mass balance VRs averaged 3.8 ± 2.0, 3.9 ± 1.8 and 5.5 ± 3.8 L s^{-1} $person^{-1}$, respectively. Scatterplots contrasting the methods showed generally good agreement with some outliers (high values from the steady-state method), and correlation coefficients from 0.74 to 0.87. Comparing transient mass balance and steady-state methods, the mean absolute deviation was 1.2 L s^{-1} $person^{-1}$, and the mean absolute relative error was 26%. The steady-state V_0 will be overestimated if the steady-state concentration is not achieved; this was seen in relatively few cases. In addition, the steady-state V_0 is sensitive to both the OA CO_2 concentration (a 10% increase to 440 ppm increased the mean V_0 by 8%) and the assumed metabolic rate (a 10% increase in the children's rate increased the mean V_0 by 8%). There was no difference in the mean or median V_0 by building type, although classrooms in ES buildings had a wider range of values and a larger number of classrooms with rates below 3 L s^{-1} $person^{-1}$ (Figure 5, right panel).

	Ventilation Rate					Percentile						
	Method	Unit	Mean	Stdev	Min	10	25	50	75	90	Max	n
ACR	Steady-state	1/h	1.22	0.60	0.27	0.51	0.76	1.06	1.60	2.06	2.92	123
	Buildup											
	Implicit Cs	1/h	1.25	0.52	0.19	0.51	0.78	1.31	1.66	1.93	2.18	123
	Midpoint Cs	1/h	1.05	0.94	0.01	0.22	0.47	0.82	1.30	2.00	7.19	109
	Transient mass balance											
	Occupied	1/h	**1.95**	**1.32**	**0.25**	**0.70**	**1.04**	**1.75**	**2.57**	**3.24**	**9.50**	**112**
	Unoccupied	1/h	0.21	0.19	0.00	0.05	0.10	0.16	0.29	0.39	1.43	131
	Decay	1/h	0.15	0.13	0.01	0.04	0.07	0.11	0.18	0.32	0.73	131
V0	Steady-state											
	Mean occupancy	L/s-person	5.63	2.70	1.87	2.53	3.64	5.56	6.96	8.41	17.65	112
	Max occupancy	L/s-person	3.81	1.99	0.98	1.54	2.29	3.38	4.79	6.47	11.61	112
	Buildup (Implicit Cs)											
	Mean occupancy	L/s-person	5.73	2.48	1.10	2.39	4.26	5.84	7.11	8.45	18.02	111
	Max occupancy	L/s-person	3.92	1.77	0.78	1.79	2.52	3.91	4.89	5.64	13.06	111
	Transient mass balance											
	Mean occupancy	L/s-person	10.07	6.91	1.98	3.14	5.68	9.14	12.13	15.83	47.07	112
	Max occupancy	L/s-person	**5.51**	**3.83**	**0.85**	**1.65**	**2.89**	**5.17**	**6.83**	**8.97**	**27.36**	**112**

Table 1. Summary of exchange and ventilation rates using the four methods. Based on 37 schools, 147 classrooms and 2-day averages in each classroom if available (decay ACR uses one day). n=number of classrooms.

Based on transient mass balance results, only 15% of the classrooms met the recommended minimum ventilation rate of 7.1 L s^{-1} $person^{-1}$ for school classrooms [17]. Even lower rates have been found elsewhere, e.g., V_0 determined using the steady-state method averaged 3.6 L s^{-1} $person^{-1}$ across 70 elementary schools in the southwest US tested in 2008-9 [10].

Figure 5. Left: Probability plot of personal ventilation rates V_0 across classrooms (based on transient mass balance method, maximum or average occupancy and 2-day average in each classroom). Right: Box plots showing V_0 by building type (based on transient mass balance method, maximum occupancy, and 2-day mean). Box plots show 10th, 25th, 50th, 75th and 90th percentiles; diamond indicates the mean.



3.5 ACRs during unoccupied periods

During unoccupied periods, ACRs determined using transient mass balance and decay methods averaged 0.21 ± 0.19 h^{-1} and 0.15 ± 0.13 h^{-1}, respectively, and were highly correlated (Spearman r=0.87; Table 1). Transient mass balance ACRs were below 0.1 h^{-1} in 32% of the classrooms. Statistically significant differences in median (but not mean) ACRs were observed by school type (median ACRs were 0.12, 0.16 and 0.19 h^{-1} in conventional, ES and LEED schools, respectively). Median (but not mean) ACRs were higher in classrooms with UVs (median of 0.19 h^{-1}) than classrooms without (0.12 h^{-1}, KW p=0.05), suggesting some leakage from these units when shut off. However, the magnitude and practical significance of these differences are small. ACRs during evening and early morning, which were far lower than those during occupied periods, reflect HVAC shutdown and suggest "tight" buildings.

Several facility managers indicated that HVAC systems were shut off immediately at the end of the school day, although they recognized that both teaching staff and maintenance staff were still working in the building. As shown in Figure 4, several buildings never "cleared" the CO_2 accumulated during the day, a result of low VRs, reflecting HVAC system shutdown and "tight" building envelopes.

Since HVAC systems were shut-off at the end of the school day, VR estimates based on CO_2 measured after midafternoon do not apply to the occupied portion of the day. Thus, neither decay rate nor transient mass balance ACRs for the unoccupied period apply to the school day.

3.6 Calculation method and applicability

VRs depended on the calculation method. During occupancy, ACRs averaged 1.2 ± 0.6 h^{-1} (average ± standard deviation) for the steady-state method, 1.2 ± 0.5 h^{-1} for the build-up method (implicit approach), and 2.0 ± 1.3 h^{-1} for the transient mass balance method (Table 1). While ACRs from steady-state and transient mass balance methods were correlated (r = 0.76), other measures of agreement showed large differences: steady-state ACRs were consistently lower (mean bias of 0.76 h^{-1}), the average relative deviation between the two methods was 44% (and often much higher), and only 29% of estimates agreed within 25%. The low ACRs given by the steady-state method reflected that steady-state conditions were not reached and that occupancy varied. Each of the methods showed reasonable day-to-day agreement, and transient mass balance, steady-state and build-up ACRs on consecutive days had Spearman correlation coefficients of 0.70, 0.67 and 0.58, respectively. The transient mass balance ACR for consecutive days differed by 22% (median absolute relative change), the smallest among the methods.

Build-up ACRs using the implicit approach to estimate the steady-state concentration were correlated to both transient mass balance ACRs (Spearman r=0.79) and steady-state ACRs (r=0.79). Like steady-state ACRs, build-up ACRs were consistently lower than the transient mass balance ACRs. In addition, build-up ACRs can be sensitive to the time period considered. Selecting the lowest concentration in the 07:00 to 09:00 period and the highest concentration in the 11:00 to 01:00 period tended to increase the build-up ACR as compared to using fixed periods; the use of longer periods (e.g., the full school day) was inappropriate since occupancy and CO_2 concentrations often decreased in the afternoon, contrary to this method's assumptions. The build-up ACR depends on the steady-state concentration, which was estimated using the room volume and the CO_2 generation rate, which in turn depended on occupancy. Overall, this method had moderate sensitivity to the time period selected. In contrast, the build-up method using the midpoint approach was very sensitive to the times selected, gave negative C_s in nearly 25% of the cases, resulted in a large range of ACRs (0.01 to 7.2 h^{-1} before cleaning), and the correlation between ACRs for consecutive days was low (r=0.14). This method failed due to the "non-ideal" CO_2 curves seen in most classrooms that resulted from changes in occupancy. Compared to the midpoint method, the implicit build-up method was more robust, though it requires some additional data (but only two CO_2 measurements).

4 Discussion

This study presents new data regarding CO_2 levels and VRs in 147 classrooms of 37 school buildings in the EQUALS study. Because the buildings were relatively new and LEED and ES buildings were disproportionately represented, the sample is not representative. Most schools are older, thus maintenance and operational issues, such as water leaks and HVAC problems, will be more common.

Elevated CO_2 levels in schools are common. As examples: In 28 schools in California, the median peak (15-min average) CO_2 concentration was 1390 ppm across 107 permanent classrooms, and 2060 ppm across 55 portable classrooms [8]; in 22 schools in Idaho and Washington, 45% of 434 classrooms had CO_2 levels above 1400 ppm (assuming an outdoor level of 400 ppm; the indoor-to-outdoor increment was reported) [4]; lower levels were reported in 10 public schools in New York State where the median CO_2 concentration was 799 ppm and only 20% of 44 classrooms studied had peak (5-min) levels exceeding 1000 ppm [19]; and in 88 Danish classrooms in 88 different schools, mean levels exceeded 1000 and 1500 ppm in 70% and 20%, respectively, of rooms tested [20]. CO_2 levels are often higher in naturally-ventilated schools. As examples: in 73 classrooms in 20 schools in Porto, Portugal, median levels exceeded 1000 ppm in 86% of classrooms [22]; in the United Kingdom, 8 of 14 classrooms in 7 schools had means above 1500 ppm [21]; and in France, CO_2 levels in 50 classrooms in 17 naturally- and mechanically-ventilated schools averaged 1400 and 1000 ppm, respectively [23].

VRs in schools have been estimated using steady-state [3, 8], decay [32], build-up [33] and simulation [5, 25, 34] methods. These studies, as well as the present analysis, show that few classrooms meet recommended minimum VRs, highlighting the gap between design or code guidelines and actual building performance. Overall, VRs in conventional and high performance school buildings did not differ. This is not surprising given the many differences among schools both within and between building types, e.g., ES buildings were typically sprawling single-floor buildings, while conventional buildings were multistory and in more urban locations. Beyond location and building typology, results may have been affected by operating practices, occupancy rates, and weather. Cost-saving factors, particularly in the ES buildings, appear to be a key driver of differences in VRs between building types. The desire for cost-savings appears to be a primary motivation for both ES certification and inappropriate practices, such as blocking outside air inlets, instructing teachers not to open windows, and the premature shutdown of mechanical systems.

We observed cleaning, maintenance, and other pollutant-emitting activities being conducted in the afternoon when HVAC systems were off, which could lead to high concentrations given the low ACRs and infiltration rates. This is an issue in both the heating season studied and in warm weather with air conditioner use since ACRs will be low to save energy and infiltration rates may further decrease given small indoor-outdoor temperature differentials [35]. Maintaining HVAC operation during these activities and possibly using a (morning) pre-occupancy purge could be beneficial. Schools have limited operating budgets and, in many cases, cleaning, maintenance (including HVAC system maintenance) and other functions have been outsourced to third parties. This may further limit local knowledge and the ability to control building system operation. It is important to ensure that ventilation is sufficient in all spaces. This may be less obvious in buildings using radiant heating or other types of systems that can provide thermal comfort with low OA flow rates. The low VRs and the inappropriate practices noted, which also included occupant behaviors such as disabling classroom ventilators, suggest that that facility managers, teachers, and principals do not understand the need for adequate ventilation and the benefits of additional ventilation with respect to children's health and academic performance.

Overall, our findings show the need to improve the understanding of the importance of ventilation. The research community should better communicate the need for adequate ventilation to school authorities, building managers, building occupants, and the broader professional community.

4.1 Limitations

Several conditions apply to our results. First, each classroom was assumed to be a single well-mixed zone that could be characterized by measurements at a central, but single location. CO_2 concentrations at representative locations should be confirmed to differ by less than 10% [28]. Second, the transient mass balance, steady-state and decay methods assumed that CO_2 levels in replacement air C_R are known. Basing CO_2 level in replacement air on OA measurements does not account for possible differences in concentrations in different portions of the building (e.g., due to contamination of intake air) or intentionally or unintentionally circulated air from contaminated indoor spaces [31, 36]. Third, build-up methods need the steady-state concentration, which was estimated using two methods. Fourth, the decay, build-up and transient mass balance methods require CO_2 measurements over a long enough period to observe meaningful concentration changes; this was rarely an issue. Fifth, while ACRs were derived when CO_2 levels exceeded instrument range, which occurred on a subset of days in several classrooms, these estimates may have larger uncertainty, although robust statistics (e.g., medians) are unlikely to be affected. Sixth, VRs vary over time (including variation within the day and across seasons) and from classroom-to-classroom, which suggests the need to utilize longer duration and seasonal sampling to obtain representative results. VRs measured in cold weather may be well below those in spring and fall seasons. Seventh, as noted, only recently-constructed or renovated and mechanically-ventilated buildings in the U.S. Midwest were studied, thus the sample may not be representative of school buildings in the country or elsewhere. Eighth, the different ACR methods were not compared to a "reference" method, such as use of injected tracer gases. Finally, this study focused on VRs and did not address other critical domains of IEQ, such as pollutant levels, thermal comfort, lighting, occupant perceptions and acoustics.

5 Conclusions

Ventilation rates (VRs) in most classrooms in the 37 recently constructed or renovated school buildings studied fell below minimum recommended guidelines. Designation as a conventional or "high performance" (EnergyStar or LEED) building was not a determinant of CO_2 concentrations or VRs. Instead, VRs were governed by the specific building and HVAC system design, maintenance and operating practices, operating schedule, teacher behavior, and other room- and school-level factors. Lower VRs were observed in classrooms and schools using UVs and radiant heating systems as compared to those using central AHUs or DOASs, and in smaller buildings and larger classrooms. In all buildings, air change rates fell to low levels when HVAC systems were shut off. Systems were often and inappropriately shutdown during cleaning and other pollutant-emitting activities in the afternoon, and several buildings did not clear the previous day's accumulation of CO_2.

VRs estimated using CO_2 as a tracer gas depended strongly on the method used, which has not been well recognized in the literature. Of the methods evaluated, the transient mass balance method using teacher-reported occupancy data proved flexible and performed well. It accommodated the variable occupancy seen in classrooms, and could estimate VRs during both occupied and unoccupied periods. VRs derived from the build-up, decay or steady-state methods had more limited application, yielded lower estimates, and results were often inconsistent, unstable, or not relevant to the occupied portion of the day.

Ventilation is a key determinant of IEQ and a potentially important factor affecting health and learning in schools. The study results, which represent conditions in relatively new and mechanically-ventilated elementary U.S. school buildings, show the need for additional ventilation in most buildings, better design and operating practices, and education regarding the importance of ventilation to the school and building community.

6 Acknowledgements

We appreciate the participation and assistance of the teachers and staff at each of the schools. We thank our research staff, including Nicole Mitchell, Julien Heidt, Sheena Martenies and An Nguyen for their assistance. This publication was developed under Assistance Agreement No. 83563701-01 awarded by the U.S. Environmental Protection Agency to the University of Michigan. It has not been

formally reviewed by EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication.

7 Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Characteristics of study schools.

Table S2. Characteristics of study schools grouped by school type.

Figure S1. Probability plot of ACRs determined using transient mass balance method during occupied and unoccupied portions of the day.

Additional information on the three example schools.

8 References

1. Persily, A., *Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62.* Building and Environment, 2015. **91**: p. 61-69.
2. Persily, A.K., *Field measurement of ventilation rates.* Indoor Air, 2016. **26**(1): p. 97.
3. Haverinen-Shaughnessy, U., D.J. Moschandreas, and R.J. Shaughnessy, *Association between substandard classroom ventilation rates and students' academic achievement.* Indoor Air, 2011. **21**(2): p. 121-131.
4. Shendell, D.G., et al., *Associations between classroom CO2 concentrations and student attendance in Washington and Idaho.* Indoor Air, 2004. **14**(5): p. 333-341.
5. Wargocki, P. and D.P. Wyon, *The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children (RP-1257).* HVAC&R Research, 2007. **13**(2): p. 165-191.
6. Sundell, J., v.J. Bronswijk, and v.F. Dijken, *Indoor environment and pupils' health in primary schools.* Building Research and Information, 2006. **34**(5): p. 437.
7. Sundell, J., et al., *Ventilation rates and health: multidisciplinary review of the scientific literature.* Indoor Air, 2011. **21**(3): p. 191.
8. Mendell, M.J., et al., *Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools.* Indoor Air, 2013. **23**(6): p. 515.
9. Rosbach, J.T.M., et al., *A ventilation intervention study in classrooms to improve indoor air quality: the FRESH study.* Environmental Health, 2013. **12**(1): p. 110.

10. Haverinen-Shaughnessy, U. and R.J. Shaughnessy, *Effects of Classroom Ventilation Rate and Temperature on Students' Test Scores.* PLoS One, 2015. **10**(8).
11. Chatzidiakou, L., D. Mumovic, and A.J. Summerfield, *What do we know about indoor air quality in school classrooms? A critical review of the literature.* Intelligent Buildings International, 2012. **4**(4): p. 228.
12. Filardo, M. *2013 State of Our Schools*. 2013 8/22/16]; Available from: http://centerforgreenschools.org/sites/default/files/resource-files/2013%20State%20of%20Our%20Schools%20Report%20FINAL.pdf.
13. US Green Building Council *LEED 2009 for Schools: New Construction and Major Renovation*. 2009.
14. Picus, L.O., et al., *Understanding the Relationship between Student Achievement and the Quality of Educational Facilities: Evidence from Wyoming.* Peabody Journal of Education, 2005. **80**(3): p. 71.
15. Carrer, P., et al., *What does the scientific literature tell us about the ventilation–health relationship in public and residential buildings?* Building and Environment, 2015. **94**(1): p. 273.
16. d'Ambrosio Alfano, F.R.e., et al., *Environment and Energy Efficiency in Schools (Part 1), REHVA Guidebook Number vol. 13*. 2010, REHVA: Brussells, Belgium.
17. ASHRAE, *Standard 62-2016 - Ventilation for Acceptable Indoor Air Quality (ANSI Approved).* . 2016, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.: Atlanta, GA.
18. Chatzidiakou, L., D. Mumovic, and A. Summerfield, *Is CO2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO2 levels, ventilation rates and selected indoor pollutants.* Building Services Engineering Research & Technology, 2015. **36**(2): p. 129.
19. Muscatiello, N., et al., *Classroom conditions and CO2 concentrations and teacher health symptom reporting in 10 New York State Schools.* Indoor Air, 2015. **25**(2): p. 157.
20. Toftum, J., et al., *Association between classroom ventilation mode and learning outcome in Danish schools.* Building and Environment, 2015. **92**: p. 494.
21. Bakó-Biró, Z., et al., *Ventilation rates in schools and pupils' performance.* Building and Environment, 2012. **48**(1): p. 215.

22. Madureira, J., et al., *Source apportionment of CO2, PM10 and VOCs levels and health risk assessment in naturally ventilated primary schools in Porto, Portugal.* BUILDING AND ENVIRONMENT, 2016. **96**: p. 198.

23. Canha, N., et al., *Assessment of ventilation and indoor air pollutants in nursery and elementary schools in France.* Indoor Air, 2016. **26**(3): p. 350.

24. Chatzidiakou, E., *Is co2 a good proxy for indoor air quality in school classrooms?* 2014, ProQuest Dissertations Publishing: University College London.

25. Wargocki, P. and D.P. Wyon, *The Effects of Moderately Raised Classroom Temperatures and Classroom Ventilation Rate on the Performance of Schoolwork by Children (RP-1257).* HVAC&R Research, 2007. **13**(2): p. 193-220.

26. U.S. Green Building Council. *Projects*. 2017; Available from: http://www.usgbc.org/projects/schools---new-construction.

27. Batterman, S., *Review and Extension of CO2-Based Methods to Determine Ventilation Rates with Application to School Classrooms.* International Journal of Environmental Research and Public Health, 2016. **In press**: p. 16.

28. ASTM, *Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation*. 2012, ASTM International: West Conshohocken, PA, USA.

29. ASTM, *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*. 2011, ASTM International.

30. WHO, *Methods for monitoring indoor air quality in schools: Report from the meeting 4-5 April 2011 Bonn, Germany*. 2011: World Health Organization, Copenhagen, Denmark. p. 32.

31. Hänninen, O., *Novel second-degree solution to single zone mass-balance equation improves the use of build-up data in estimating ventilation rates in classrooms.* Journal of Chemical Health and Safety, 2013. **20**(2): p. 14.

32. Turanjanin, V., et al., *Indoor CO2 measurements in Serbian schools and ventilation rate calculation.* Energy, 2014. **77**: p. 290.

33. Hänninen, O., et al., *Evaluation of ventilation rates in European schools using CO2 measurements as part of a proposed WHO school survey*, in *Healthy Buildings*. 2012: Brisbane, Australia. p. 845.

34. Scheff, P.A., et al., *Indoor air quality in a middle school, part I: Use of CO2 as a tracer for effective ventilation.* Applied Occupational and Environmental Hygiene, 2000. **15**(11): p. 824.

35. Breen, M.S., et al., *A review of air exchange rate models for air pollution exposure assessments*. Journal of Exposure Science and Environmental Epidemiology, 2014. **24**(6): p. 555.

36. Hänninen, O. *Combining CO2 data from ventilation phases improves estimation of air exchange rates*. in *Healthy Buildings*. 2012. Brisbane, Australia.