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Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation

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ABSTRACT

Previous research has shown that under-ventilation of classrooms is common and negatively impacts student health and learning. To advance understanding of contributing factors, this study visited 104 classrooms from 11 schools that had recently been retrofitted with new heating, ventilation, and air-conditioning (HVAC) units. CO_2 concentration, room and supply air temperature and relative humidity, and door opening were measured for four weeks in each classroom. Field inspections identified HVAC equipment, fan control, and/or filter maintenance problems in 51% of the studied classrooms. Across 94 classrooms with valid data, average CO_2 concentrations measured during school hours had a mean of 895 ppm and a standard deviation (SD) of 263 ppm. Ventilation rates (VRs), estimated using the daily maximum 15-min CO_2 in each classroom, had a mean of 5.2 L/s-person and a SD of 2.0 L/s-person across 94 classrooms. Classrooms with economizers, with or without demand control ventilation (DCV), tended to have lower mean CO_2. Improperly selected equipment, lack of commissioning, incorrect fan control settings and maintenance issues (heavily loaded filters) were all associated with under-ventilation in classrooms. Many classrooms in this sample were frequently too warm to support learning. There were 23 out of 103 classrooms that had indoor air temperature above 25.6 °C for more than 20% of the school hours. Better oversight on HVAC system installation and commissioning are needed to ensure adequate classroom ventilation. Periodic testing of ventilation systems and/or continuous real-time CO_2 monitoring (either as stand-alone monitors or incorporated into thermostats) is recommended to detect and correct ventilation problems.

1. Introduction

Many studies have documented that inadequate ventilation in classrooms is common and some have investigated the association between ventilation and health or performance, as summarized in several recent reviews [1–3]. After compiling summary CO_2 concentrations from 26 studies worldwide with measurements from 20 or more classrooms, Fisk (2017) concluded that ventilation rates (VRs) in classrooms are often below the minimum rates required by building standards [2]. The review by Fisk presented compelling evidence of an association between VRs and student performance, respiratory health effects, and student absence. Eight of the eleven studies reviewed found associations between VRs or CO_2 concentrations and at least some measures of student performance, e.g., using students' scores on standard academic achievement tests or special tests administrated by the researchers. Four of five studies found statistically significant decreases in absence rates with more ventilation or lower CO_2 concentrations. Based on this body of research, increasing VRs in classrooms to meet the minimum requirement is expected to improve student performance, attendance, and health.

Minimum VR standards are established to balance good indoor air quality and energy efficiency. In the United States, ASHRAE Standard 62.1 Ventilation for Acceptable Indoor Air Quality [4] defines the minimum VR for classrooms as 7 L/s-person (15 CFM/person), which is the combined per-person and per-floor area requirement calculated using a default occupant density. In California, the Building Energy Efficiency Standards (Title 24) [5] has the same ventilation requirement for classrooms. Mendell et al. (2013) measured VRs in 162 California classrooms and found that most were ventilated at rates lower than the required 7 L/s-person [6]. Estimated mean VRs based on measured

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15-min peak CO_2 was only 3.5 L/s-person among the group of classrooms with mechanical ventilation and air conditioning. In the Central Valley, where all 51 studied classrooms were mechanically ventilated with air conditioning, only 5% of the 51 studied classrooms had ventilation meeting the 7 L/s-person requirement.

Despite the well-documented problem of under-ventilation in classrooms, it is not clear why this problem is so frequent and why it persists. Batterman et al. (2017) reported that cost-saving measures, such as blocking the outside air damper of the heating, ventilation, and air conditioning (HVAC) system, partly explained why only 22% of the 37 recently constructed or renovated classrooms met recommended minimum ventilation rates [3]. The review by Fisk commented on a lack of systematic data which is needed for school districts and facility managers to correct the problem [2].

Aside from inadequate ventilation, thermal discomfort is also a common problem among classrooms. Wargocki and Wyon (2013) reviewed studies of environmental effects on performance of schoolwork and suggested that children are more susceptible than adults to environmental conditions [7]. The effects of air temperature on student performance may be caused by the distraction and/or physiological effects of thermal discomfort. A recent review [8] concluded that student's thermal preferences were not within the comfort range provided by commonly used thermal comfort standards, such as ASHARE Standard 55 [9]. Reviewed studies showed that students prefer cooler temperature than expected for adults, and they are more sensitive to warmer conditions. Wargocki et al. (2019) determined the relationship between classroom and children's performance in school and found that in temperate climates such as the US, the optimal temperature is lower than 22 °C [10]. Haverinen-Shaghnessy et al. (2015) analyzed indoor environmental quality parameters (including temperature, relative humidity, and CO_2) and students' performance, absenteeism, and health data in 70 elementary schools in southwestern US [11]. Significant associations were observed between students scoring in mathematics and reading tests with indoor temperature, as well as with ventilation rate in classrooms. Regression analysis [11] found that schools with lower than mean indoor temperature (23 °C) and higher than mean ventilation rate (3.6 L/s-person) have significantly (13–14%) higher percentage of students scoring satisfactory in the mathematics and reading tests compared to schools with higher than mean indoor temperature and lower than mean ventilation rate.

The study reported herein aimed to advance understanding of the factors that contribute to under-ventilation and to explore whether the problem also occurs commonly in classrooms. We deployed monitors to measure CO_2 concentrations and other indoor environmental parameters in 11 California K-12 schools. A total of 104 classrooms were monitored for approximately 4 weeks each. We also performed field inspections to identify potential problems with hardware, control, and filter maintenance of the HVAC systems. All 104 studied classrooms had an HVAC system that was replaced within the prior three years (2013–2016); we were thus able to gather information from facilities staff with knowledge about the retrofit and any identified issues with system operation, performance, and maintenance. In addition, we conducted a teacher survey, asking about their satisfaction with classroom indoor environmental quality and their impression of the HVAC system. This paper focuses on results of the CO_2 monitoring and estimates of ventilation rates. In addition, we also present results of the indoor air temperature measurements in the 104 classrooms because temperature can significantly impact comfort and student performance.

2. Method

2.1. Study sample

The main approach for identifying candidate schools was to search a database of projects supported by the California Clean Energy Jobs Act (Proposition 39, 2013–2017). The program provided subsidies for upgrade packages that met specified savings to investment ratios. We searched the database for K-12 public schools that purchased and installed at least five, single-zone HVAC replacement units in classrooms within the prior three years. To broadly represent the diversity of K-12 schools in California, we identified both small and large school districts, schools in rural and urban areas, and student bodies with different household incomes. Within each category, preference was given to the schools that had more classrooms retrofitted with new HVAC units. Recruitment typically started with an email sent to the point of contact listed on the funding application. Additional emails were sent and phone calls made until we reached an appropriate contact person, such as a Director of Facilities or Energy Manager, who could confirm eligibility and was willing to work with us to secure internal approvals for a school or district to participate. We worked with the contact person to select a group of instructional classrooms (excluding science labs, art studios, and other special purpose rooms) for inclusion in the study. The University of California Davis Institutional Review Board approved the study protocol.

2.2. HVAC characteristics

A field team characterized the HVAC system in each of the selected classrooms at the start of the 4-week monitoring period for the school. They documented the location (roof top or wall-mount), type of heating system (gas or electric heat pump), make and model, rated capacity and efficiency of the HVAC system (Table A-1 in Appendix). The team also assessed the functional and operational state of the ventilation system, the presence of an energy management system, and temperature setpoints. Ventilation rates were measured using a flow hood in a subset of classrooms (Table A-2). The field team visually inspected the air filter and recorded its efficiency rating and condition.

2.3. CO_2 monitoring

CO_2 was measured by infrared absorption using Vaisala (Finland) CARBOCAP GMW86/94 wall-mounted sensors. Sensors with a range of 0–2000 ppm were used in Schools 1 and 2. After observing readings of CO_2 routinely exceeded 2000 ppm in these schools, sensors with a range of 0–5000 ppm were used in the remaining nine schools (3−11). Temperature and relative humidity (RH) were measured and recorded with Onset (Massachusetts, USA) HOBO U12 data loggers, which also logged CO_2 readings, at 3-min intervals. The CO_2 sensors were installed at a location at least 1.5 m away from doors, windows, and supply air outlets (Fig. 1). An additional HOBO data logger with temperature and RH sensors was installed on the supply air grille in each classroom to track heating and cooling system operation. Door opening status was monitored and recorded using a HOBO UX90 state data logger.

All CO_2 sensors were purchased new from the manufacturer at the start of the study and calibrations were checked at the start and end of the study. In the calibration process, CO_2 was injected into a test chamber to reach a concentration of approximately 5000 ppm then allowed to decay to 500 ppm. CO_2 sensor output voltage measured during this calibration process was compared against the concentrations measured using an EGM-4 CO_2 analyzer (PP Systems, Massachusetts, USA). The EGM-4 CO_2 analyzer readings were checked using a certified standard gas with 2466 ppm CO_2 and at five dilutions with air containing no CO_2. We calculated the difference in CO_2 sensor response at a setpoint of 1000 ppm by comparing the before and after calibration. The mean difference equaled 12 ppm, with a standard deviation of 21 ppm for 53 paired comparisons.

2.4. Analysis of CO_2 data and calculation of ventilation rate

All analyses of CO_2 concentrations and indoor air temperature are limited to school hours according to the official bell schedule. CO_2 data suggests that some classrooms were routinely occupied for additional

Fig. 1. Sensors deployed in schools to measure room CO_2, air temperature and RH (left), supply air temperature and relative humidity (middle), and door open/close state (right).

hours, such as during after-school activities. These additional occupied hours were not considered in our analyses, even though it is a requirement to provide ventilation during all periods of occupancy.

A per-person ventilation rate, VR, was estimated for each school day using the mass balance model presented in Eq. (1).

$$VR = \frac{E}{C_{15max} - C_o} \tag{1}$$

where VR is the ventilation rate per person (L/s-person), E is the CO_2 generation rate per person (L/s-person), C_{15max} is the daily maximum 15-min average classroom CO_2 concentration (ppm), and C_o is the outdoor CO_2 concentration (ppm), assumed to be 400 ppm based on California's Title 24 [5]. Monitoring studies in two urban areas of California (Los Angeles and Oakland) found mean C_o varied between 400 ppm and 440 ppm [12,13]. The assumed C_o is a source of uncertainty in our VR estimates.

Eq. (1) uses the highest 15-min average CO_2 as an estimate of steady-state conditions. Visual review of the data found that the highest 15-min average did not always present as a steady-state condition. This is because changes in CO_2 emissions as a result from changing occupancy during school hours occur roughly on the same time scale as ventilation rate (typically 1–3 air changes per hour). If the same outdoor airflow was provided throughout the day, lower CO_2 concentrations recorded during other periods would indicate fewer students in the room and therefore higher VR per person. In other words, VR calculated with Eq. (1) would represent a lower-bound estimate of the per-person VR for the day in this case. However, if the CO_2 was increasing during the highest 15-min average (i.e. steady state not reached), the calculated VR would be biased high relative to the actual rate at the time. With cognizance of the uncertainties noted above, we subsequently refer to the VRs calculated with Eq. (1) as estimated VRs, or simply VRs.

Batterman (2017) reviewed several methods for estimating classroom VR [14]. The review concluded that if the time-varying attendance is known, the transient mass balance method typically provides the most consistent and accurate results. This study did not use the transient mass balance method because daily attendance was not monitored. Steady-state method was used instead, which only differed from the transient mass balance method by 10% on average [14]. Another reason for using the steady-state method in this study is that the calculated VRs can be directly compared with prior studies that estimated VRs using the same method, including the study of 162 California classrooms previously mentioned [6].

For the per-person emission rates E, we used values for each grade level from pre-K (0.0025 L/s-person) to 12th grade (0.0057 L/s-person) [14]. The grade level of students in each classroom was determined from the teacher survey and information gathered from the site visit. We compared the values used in this study with those presented by Persily and Jonge (2017) [15]. Our VR estimates would be very similar for students in lower grades, but slightly lower for upper grade classrooms, had we used the emission rates from Persily and Jonge (2017).

2.5. Analysis of classroom air temperature

We calculated mean air temperature during school hours and compared with the recommended range (20–23 °C) that prior studies [7, 11] had suggested is associated with improved student performance, relative to warmer temperature. We also calculated the percentage of school hours outside of the typical range of 20–25.6 °C (68–78 °F) for the comfort of occupants. A detail thermal comfort analysis would require more data from the occupants as well as measurements of indoor environmental parameters that is beyond the scope of this study. The simple calculation of % school hours outside of 20–25.6 °C is still informative to see if the studied classrooms experienced conditions that were likely too cold or too warm to its occupants.

3. Results and discussion

3.1. Classroom characteristics

Table 1 summarizes the characteristics of the schools included in this study. The schools were located in northern, southern, coastal and inland areas of California. All schools were public, and one was a public charter school. Six to 15 classrooms from each participating school were studied. About two-thirds of the classrooms were in permanent, site-

Table 1
Characteristics of the districts and schools in the study.

School	School District Enrollment Size[a]	County (Climate Zone)	Grade Levels Monitored	Permanent Classrooms	Portable Classrooms
1	Large	Riverside (10)	K-12	–	8
2	Large	San Joaquin (12)	6–8	–	10
3	Large	Orange (8)	K	6	–
4	Large	Orange (8)	1–5	10	–
5	Small	Glenn (11)	9–12	10	–
6	Medium	Contra Costa (12)	1–5	10	–
7	Medium	Yolo (12)	K-6	10	5
8	Small	San Mateo (3)	6–8	10	–
9	Medium	Orange (6)	1–5	10	–
10	Medium	Alameda (3)	9–12	–	6
11	Medium	Alameda (3)	1–6	5	4
Total				**71**	**33**

[a] District enrollment from California Department of Education website: http://www.cde.ca.gov/schooldirectory/Size categories are: small (<5,000 students), medium (5,000 to 15,000), and large (>15,000).

constructed buildings; the others were in relocatable or portable classrooms. The sample was weighted to lower grades, with 42 of the classrooms from 7 schools serving grades K-3, and 43 classrooms from 8 schools assigned to grades 4–8. Only 19 of the 104 classrooms were occupied by upper grades (9–12), and 16 of those where from the two high schools (Table 1). The studied classrooms had a mean floor area of 83 m^2 (range of 67–102 m^2). The mean class size was 28 students (range of 14–37), which is typical for California classrooms. All 104 classrooms were generally in good condition based on visual inspection. The field team did not observe any visible mold. Evidence of pests (e.g., cockroaches) was reported in two classrooms.

Four schools (3–6) were monitored during the heating season of late November 2016 through March 2017. The other seven schools were monitored during the cooling and shoulder seasons of September through early November 2016 (schools 1–2), and April through June 2017 (schools 7–11). Whether the HVAC systems were operating in heating and/or cooling mode was determined based on the supply air temperature (see Figure A-1 in Appendix). Schools 1 and 8–11 were cooling dominated. Both heating and cooling occurred when schools 2 and 7 were monitored.

3.2. HVAC equipment and system controls

The study included 63 rooftop units (RTUs) and 41 wall-mount HVAC systems. Most of the portable classrooms (31 of 33) had wall-mount systems and most of the permanent classrooms (61 of 71) were serviced by an RTU. All wall-mount units used electric heat pumps, whereas all but two RTUs used gas heating. The RTUs had higher efficiency ratings (EER 11.2–13.0) than the wall-mount heat pumps (EER 9.0–11.0).

The ventilation systems can be divided into five technology groups. The HVAC units serving 19 classrooms with "fixed position ventilator" systems could provide the code-required VR per Title 24 if configured correctly. These systems have a damper for outdoor air that is either continuously open or is powered to open to a fixed stop position when the air handler fan operates, and also have an exhaust air path for pressure relief from the room. Six classrooms had non-powered, spring-based outdoor air dampers without an exhaust air pathway for pressure relief; this equipment is designed for spaces with lower outdoor air requirements (such as modular offices with lower occupant density) and cannot provide the code-required ventilation for 30 students and a teacher even when set to the maximum opening position. Five of the HVAC systems had energy recovery ventilators (ERV) that provide constant, balanced (supply and exhaust) airflows that transfer sensible and latent heat through an enthalpy wheel. Seventy-four systems were equipped with economizer units that use outdoor air in place of mechanical cooling when the outdoor air temperature or enthalpy is below a set value. These units had the capacity to pull up to 100% of the air that they supply to the room from the outdoors. Twenty-five of the systems with economizers were additionally equipped with a controller that modulates the outdoor air to maintain CO_2 concentrations below a set value based on sensor readings in the room, a strategy called demand control ventilation (DCV).

The field inspection found incorrect equipment or other serious installation problems in 16 classrooms. The field team measured outdoor airflow for the six ventilator systems with non-powered, spring-based outdoor air dampers and found that they provided very little ventilation (range of 0–40 L/s; mean of 17 L/s (35 CFM)). In three of the systems with the fixed position ventilator, the low voltage electric power and control signal were not connected, so the outdoor air damper was always closed. Seven of the economizer (without DCV) systems were wired incorrectly or were not configured properly such that they were always closed. No obvious hardware problems were found in the systems with either DCV or an ERV. However, it is possible that installation problems were under reported because our field team did not directly measure outdoor airflow or check the damper position setting in all classrooms. Therefore, the absence of an identified problem does not mean that the VR to the classroom was sufficient. Estimated VRs by ventilation system are provided in a later section.

Most of the classrooms (96 of 104) had a thermostat that was networked to an energy management system (EMS), where the school district controlled the allowable heating and cooling setpoint range and fan operation schedule. Facilities staff reported typical heating setpoints ranging between 17.8 °C and 20.6 °C (64 °F and 69 °F), and cooling setpoints ranging between 22.2 °C and 24.4 °C (72 °F to 76 °F). Eight classrooms had no EMS. In 79 of the 96 classrooms with an EMS, the teacher had some control of room temperature within a range set by the school district. For example, teachers could adjust setpoints by 1.1 °C–2.2 °C (2 °F to 4 °F). The thermostat had a manual override button, enabling heating/cooling and ventilation for 30–60 min at a time outside of the scheduled occupied hours. In the other 17 systems linked to an EMS, the teacher had no control of room temperature. All of the equipment examined in this study requires the ventilation fan to run continuously during occupied hours to deliver adequate ventilation for a classroom with approximately 30 students and a teacher. However, in 22 classrooms, the ventilation fan was incorrectly set to "auto" mode and operated only when the system was heating or cooling. This occurred in classrooms with and without an EMS. One classroom without EMS had the fan set to run continuously (24/7). In this case, the thermostat was locked so that the teacher could not turn off the fan.

3.3. Filter characteristics

California's Title 24 [5] requires that all commercial buildings, including schools, use filters with a MERV (minimum efficiency rating value) of 6 or higher. The majority of the classrooms (85 of 104) had 2-inch pleated air filters with either a MERV 7 or MERV 8 rating. About one-third of the classrooms with wall-mount system (13 out of 41) had non-pleated polyester media filters with no MERV rating. One RTU had no air filter. It was unclear why the filter was missing; similar classrooms and equipment inspected at the same school all had air filters. Three air filters in wall-mount units could not be evaluated because they were inaccessible (the screws on the filter compartment cover could not be removed).

The condition of each filter was rated on a scale of 1 (like new) to 5 (past service life) by visual inspection. An example photo for each rating level is provided in the Appendix (Table A-3). Thirty of the 100 filters that could be inspected fell into categories 4 and 5, and most of these (26 of 30) were found in wall-mount units.

3.4. Occurrences of HVAC problems

Table 2 shows the number of occurrences of each of the common HVAC problems observed in the study.

- Hardware: Inadequate ventilation equipment and/or improper installation resulting in no or minimal outside air to the classroom.
- Controls: Fan not operating continuously during occupied hours, resulting in reduced fan run hours and reduced outside air to the classroom.
- Maintenance: Filter is due for change or past service life, possibly resulting in reduced airflows and reduced outside air to classroom.

More than half of the classrooms had at least one problem identified. Problems were more commonly found in wall-mount units (93% had one or more problems) than RTUs (24%). Ventilation systems with economizer only or economizer + DCV had fewer problems identified during field inspection, in comparison to the other ventilation system types. The low frequency of problems in the 25 classrooms with economizer + DCV may result from those systems being in two districts with full-time energy managers who were involved with HVAC equipment installation and commissioning. Also, the DCV systems collected and reported CO_2

Table 2
Summary statistics of HVAC problems that could result in inadequate classroom ventilation.

Problems: Hardware (H), Control (C), and/or Filter (F)	HVAC Type		Ventilation System Type					Total
	RTU	Wall-Mount	Fixed Position Ventilator	Low-Flow Spring Damper	ERV	Econo-mizer	Econo-mizer + DCV	
None identified	48	3	4	–	–	23	24	51
Hardware only	2	3	1	–	–	4	–	5
Control only	7	6	7	–	–	6	–	13
Hardware + Control	1	–	–	–	–	1	–	1
Filter only	3	14	4	–	4	8	1	17
Hardware + Filter	–	9	2	6	–	1	–	9
Control + Filter	1	6	1	–	1	5	–	7
H + C + F	1	–	–	–	–	1	–	1
Total	63	41	19	6	5	49	25	104

data to the facilities staff, so ventilation problems can be easily identified and fixed.

3.5. CO_2 concentration and ventilation rate

Fig. 2 shows the distribution of mean CO_2 concentrations across classrooms measured during school hours. Also shown is the distribution of the means of the 15-min highest daily average CO_2 concentrations. Because of data loss in 10 classrooms (e.g., power unplugged), data from only 94 classrooms were available for this analysis. The mean and median CO_2 concentrations across all measurements during school hours were 895 ppm and 897 ppm, respectively. The distribution of the mean concentration plotted in this figure assumed the value of 2,000 ppm during times when CO_2 concentrations exceeded this upper limit in schools 1 and 2. Among the 18 classrooms from those two schools, 8 had CO_2 concentrations above 2,000 ppm for a substantial amount of the time, varying from 17% to 69% of the occupied hours. As a result, the plotted distributions likely underestimate the true CO_2 statistics of the classrooms measured.

California's Title 24 [5] has no requirement to maintain CO_2 below a specified concentration. However, as a reference point, we considered the CO_2 concentration that would occur in spaces that meet the minimum VR requirement of 7 L/s-person. For a CO_2 generation rate of 0.005 L/s-person (corresponding to 7-8th grade students), a space ventilated at the Title 24 minimum would have a steady-state CO_2 concentration of 1100 ppm, or 700 ppm above the concentration of CO_2 (400 ppm) in outdoor air. Fig. 3 shows the percent of time when CO_2 concentrations exceeded 1100 ppm in each classroom. There were variations across classrooms within each school and big differences

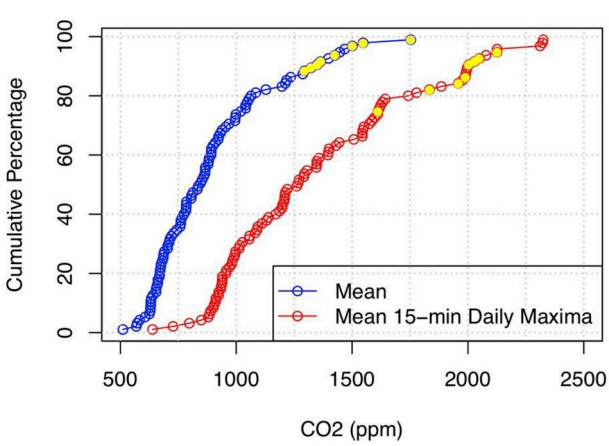

Fig. 2. Indoor CO_2 concentrations measured during school hours in 94 classrooms. Yellow circles indicate classrooms that frequently had CO2 at or above the sensor limit of 2000 ppm; the values presented for these 8 classrooms may therefore be biased low. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

between schools. This shows that in schools where under-ventilation is a problem, it tends to occur not as an isolated case, but rather as a common problem that affects many classrooms within a school. Based on interviews with facilities staff, the problem of inadequate ventilation is largely not detected.

The VR was calculated using Eq. (1) for each classroom during each school day of monitoring. Fig. 4 shows the distributions of the mean and median of the calculated daily VRs for each classroom. Across the 94 classrooms with CO_2 data, the 50th percentiles of mean and median VR were 5.2 L/s-person and 4.8 L/s-person, respectively. Only around 15% of the classrooms had a median of daily VR estimates that met the 7 L/s-person code requirement. More detailed statistics of the estimated VR (interquartile range, 5th and 95th percentile values) categorized by classroom characteristics are provided in the Appendix.

3.6. Relationship between CO_2 concentration, VR, and HVAC characteristics

Mean, 5th and 95th percentiles of the estimated VRs and measured CO_2 concentrations were calculated by grade level, building type, HVAC type, ventilation system type, filter conditions, identified HVAC problems, and duration of door opening. Table 3 provides the results and comparisons by sub-group using Tukey Honest Significant Difference tests, which is a single-step statistical test for multiple comparisons. The p-values show the significance in difference in means between each sub-group with respect to a reference (always the first listed in the table). Statistical tests were performed using "TukeyHSD" in R [16]. Additional boxplots are provided in the Appendix (Figure A-3 to A-8).

The estimated VRs for the three grade levels (K-3, 4–8, and 9–12) were not statistically different from one another. There were classrooms across all grade levels with estimated VRs below the code requirement of 7 L/s-person. However, mean CO_2 concentrations were significantly higher in the middle (4–8: mean = 985 ppm) compared to the other grades. This is likely because middle grade classrooms studied had on average a greater number of students (mean = 30), compared to the other grades (mean = 26 in lower grades, mean = 28 in upper grades).

Classrooms with RTUs had higher estimated VRs, and lower mean CO_2 concentrations, than those with wall-mount systems. The differences in means are statistically significant at the 0.05 level. Because portable classrooms predominately (31 out of 33) used wall-mount HVAC systems, and permanent classrooms predominately (61 out of 71) used RTUs, differences in mean estimated VR and CO_2 are similar if results are categorized by building type. The previous study of 162 California classrooms [6] also reported that permanent classrooms had higher ventilation rates than portable classrooms. A study of 201 classrooms in California [17] found that portable classrooms had more HVAC problems, including blocked air dampers, dirty air filters, and excess noise that resulted in the ventilation system being turned off by teachers in portable classrooms.

Estimated VRs were lower among the small number of classrooms (N = 5) with ERVs. This may be attributable to the poor condition of the

Fig. 3. Percent of time during school hours when measured CO_2 concentration exceeded 1100 ppm. Each bar represents a classroom. Data is missing from 10 classrooms because of sensor or data logging problems.

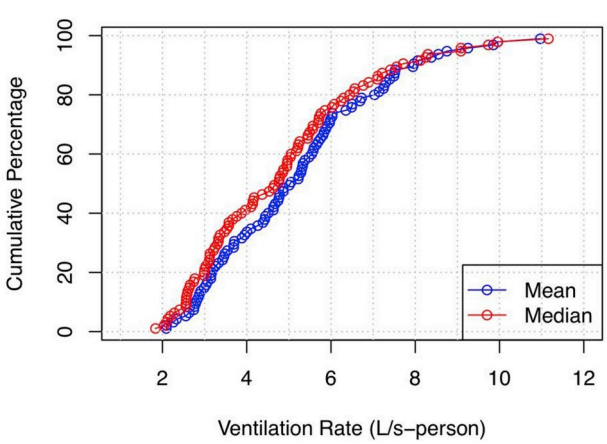

Fig. 4. Cumulative probability of mean and median of daily estimates of ventilation rates in 94 classrooms. California's Title 24 ventilation requirement is 7 L/s per person.

air filters in the units: three had non-pleated polyester media filters with a rating of 4 (time to change) and the filters in the other two were inaccessible for inspection (and presumably less likely to be maintained) because the hatch screws were stuck. It is also possible that there was a problem with the ERV system function that was not detected during the field inspection. The classrooms with low airflow spring damper systems did not have measured CO2 or mean estimates of VR that were significantly different from those with fixed position ventilators; but since there were so few classrooms (N = 5) with the spring damper equipment and valid CO_2 data this result should not be considered as robust.

Classrooms with economizers, with or without DCV, had lower mean CO_2 concentrations than classrooms with fixed position ventilators, but VR estimates were comparable. This makes intuitive sense because economizers can bring in more outdoor air when cooling is required and outdoor conditions are conducive, thus resulting in lower CO_2 concentrations at those times. Mean VRs in classrooms with economizers were not significantly lower than VRs in classrooms with fixed position ventilators; this could be because the daily highest 15-min CO_2 concentrations used to compute the VRs may not have occurred when the economizers were in operation. Classrooms with DCV all had CO_2 below 1000 ppm, suggesting that DCV was functioning as intended to modulate ventilation as needed.

Classrooms with filters that were substantially soiled (rating 3 to 5) tended to have lower VRs and higher mean CO_2 concentrations on average than classrooms with relatively clean air filters (rating 1 and 2). As mentioned earlier, past-life air filters were more common in classrooms with wall-mount units than RTUs. Past-life filters are also more

Table 3
Summary statistics for estimated VR and mean CO_2 grouped by classroom and HVAC system characteristics.

Classroom/HVAC Characteristics		N	Estimated VR (L/s-person)		Mean CO_2 (ppm)	
			Mean (5th– 95th %tile) [a]	p-value [b]	Mean (5th– 95th %tile) [a]	p-value [b]
All Classrooms with CO_2 Data		94	5.2 (2.6–8.6)	–	895 (619–1433)	–
Grade Level	K-3	40	5.1 (2.2–8.8)	–	797 (582–1198)	–
	4–8	36	5.0 (2.7–8.1)	9.7E-01	985 (624–1513)	4.4E-03*
	9–12	18	5.7 (3.2–8.7)	5.4E-01	933 (661–1345)	1.4E-01
Building Type	Portable	32	4.0 (2.3–7.2)	–	1111 (676–1522)	–
	Permanent	62	5.7 (2.9–8.7)	4.0E-05*	784 (608–1063)	8.0E-10*
HVAC Type	Wall-Mount	38	4.2 (2.3–7.6)	–	1068 (693–1508)	–
	RTU	56	5.8 (2.9–8.9)	2.8E-05*	778 (601–1052)	1.5E-08*
Ventilation System Type	Fixed Position Ventilator	19	4.7 (2.3–8.7)	–	1040 (661–1568)	–
	Low Airflow Spring Damper	5	5.5 (3.2–8.1)	9.2E-01	903 (714–1217)	7.3E-01
	ERV	5	3.2 (2.3–4.1)	5.2E-01	1390 (1295–1501)	1.8E-02*
	Economizer	44	5.4 (2.8–9.2)	6.9E-01	829 (574–1219)	6.7E-03*
	DCV + Economizer	21	5.4 (3.2–7.3)	7.6E-01	783 (632–924)	3.5E-03*
Filter Condition (N = 91)	1 = Like new	20	6.6 (2.9–9.3)	–	776 (605–1030)	–
	2 = Clean	33	5.7 (3.1–9.1)	3.0E-01	757 (579–963)	1.0E+01
	3 = Used	12	4.1 (2.4–5.4)	7.9E-04*	995 (697–1522)	5.0E-02*
	4 = Time to change	23	4.2 (2.4–7.4)	8.1E-05*	1059 (718–1442)	4.2E-04*
	5 = Past service life	3	3.4 (2.8–3.9)	2.2E-02*	1177 (1048–1426)	2.8E-02*
HVAC Failures	None	47	6.1 (3.2–9.7)	–	748 (576–950)	–
	Hardware/Control Problems	18	4.5 (2.6–6.8)	5.1E-03*	961 (697–1357)	3.1E-03*
	Hardware/Control + Filter	14	4.5 (2.8–7.7)	1.4E-02*	1094 (710–1541)	5.2E-06*
	Filter Problem Only	15	3.5 (2.2–4.7)	9.8E-06*	1093 (813–1453)	5.2E-06*
Door Opening (N = 89)	<20% of School Hours	41	5.1 (2.8–7.5)	–	880 (631–1350)	–
	20–50%	27	5.0 (2.3–9.0)	1.0E+0	913 (614–1395)	8.6E-01
	>50%	21	5.5 (2.8–8.8)	7.0E-01	910 (573–1468)	9.0E-01

[a] Sample percentiles (5th and 95th) obtained by linear interpolation between values. For N < 10, minimum and maximum values were presented instead.
[b] p-value from Tukey Honest Significant Difference test comparing classrooms of different characteristics with respect to the first subgroup within each set of characteristics. "*" means significant at the 0.05 level.

commonly associated with classrooms with fixed position ventilators, low airflow spring dampers, or ERVs than classrooms with economizers with or without DCV.

Fig. 5 shows results for the classrooms with one or more problems identified from HVAC inspection during site visits. Classrooms with any one or more of the HVAC problems tended to have lower VRs and higher mean CO_2. The difference in mean estimates are statistically significant at the 0.05 level in all cases, with respect to classrooms with no observable problems. We found no statistically significant difference in the mean estimates between classrooms that had hardware and/or control problems alone, and classrooms that had hardware and/or control in addition to having filters due for change or past service life. This result is expected: if the HVAC system is not providing sufficient ventilation because of hardware and/or control problems, the filter condition may not be as important. On the other hand, heavily loaded air filters alone are associated with lower VRs and higher mean CO_2. A possible explanation is that HVAC systems with heavily loaded air filters also had other problems that was not identified during the field inspection, such as incorrect damper position setting resulting in inadequate ventilation. It is also possible that heavily loaded air filters can reduce airflow and outdoor air ventilation for some HVAC systems. However, we did not perform additional test to confirm this.

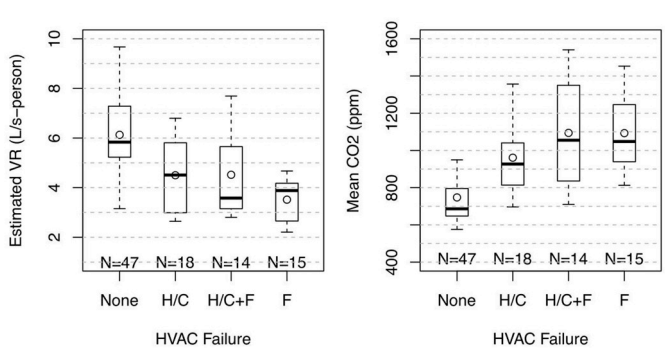

Fig. 5. Estimated VR and measured mean CO_2 across classrooms, grouped by failures observed during HVAC inspection: H/C = hardware and/or control problems, F = filter due for change or past service life (rating 4 or 5). The box shows the interquartile range (25th and 75th percentiles); whiskers extend to 5th and 95th percentiles; thick line inside box is the median; and open circle is the mean. N = number of classrooms.

Door opening can increase the rate of outside air flowing into a classroom. The door state data show that the lower grade (K-3) classrooms tended to keep their door closed most often (percentage of time with door opened during school hours: mean = 24%; median = 15%) compared to the middle grades (mean = 36%; median = 25%) and the upper grades (mean = 45%; median = 53%). This pattern of door opening reflects how classrooms are occupied. Lower grade (K-3) classrooms are more commonly occupied by the same class of students through the school day, so the need to open doors is less compared to upper grades (9–12) where students attend classes in different classrooms throughout the school day. Overall, we observed no apparent relationship between the measured CO_2 concentrations, or the estimated VRs, and the percentage of time a classroom left the door opened. Table 3 shows that there is no difference in the mean values between classrooms with a door open at moderate (20–50%) or high frequency (>50%), relative to classrooms that opened a door less than 20% of the time during school hours. It is possible that classroom doors were not opened wide enough to affect ventilation. It may also be that doors were opened more frequently in classrooms that were not adequately ventilated, in an effort to compensate for a deficiency of the ventilation equipment. In any case, this result points to the importance of mechanical ventilation to ensure sufficient ventilation, because door opening alone does not appear to bring in enough outside air to impact the CO_2 concentrations measured in classrooms.

3.7. Classroom air temperature

The mean indoor temperatures measured during school hours in the 103 classrooms (temperature and humidity data was lost for 1 classroom) was 23.3 °C and the range across classroom means was

19.3–26.4 °C. The mean RH was 48% and the range of mean RH across classrooms was 33–64%. About 60% of the classrooms monitored in this study were warmer than the recommended temperature range based on student performance research [7,11]. Mean temperature above 23 °C were measured in both the heating and cooling seasons, as well as the shoulder season (Table 4). More detailed statistics for the measured indoor temperature and relative humidity are provided in the Appendix (Table A-6).

Fig. 6 shows the percent of school hours where indoor air temperature was outside of the typical range for thermal comfort, 20–25.6 °C (68–78 °F). The majority of the classrooms with a large percent of school hours outside the desired thermal comfort range was because of indoor air temperature being too warm (>25.6 °C). There were 23 classrooms with indoor air temperature above 25.6 °C for more than 20% of the school hours. In comparison, classrooms with indoor air temperature below 20 °C for more than 20% of the school hours were found in only five classrooms.

Teachers were asked for their opinion about thermal comfort in both the cooling and heating seasons and they expressed dissatisfaction in both. About 30% of teachers who responded to the survey were "dissatisfied" or "very dissatisfied" with air temperature in their classroom in either season. Some teachers reported taking actions (e.g., constantly adjusting thermostat settings throughout the day) in response to the temperature fluctuations both temporally and spatially within the classrooms. About 10% of teachers said air temperature "interferes a lot" with the learning environment. More detailed statistics on the responses from the teacher survey about temperature in classrooms are provided in the Appendix (Figure A-9).

4. Discussion

Table 5 compares results from this study with relevant prior studies taken from a recent review paper [2] and two additional studies published since the review on classroom CO_2 and VRs in the United States. VRs estimated from this study are higher, and CO_2 concentrations are in the lower range of the values reported in the literature. Overall, the California classrooms with recently retrofitted HVAC equipment in this study showed some improvements in terms of higher VRs compared with a previous study in California [6]. However, the VRs of many classrooms are still below the requirements of the ASHRAE 62.1 standard and California's Title 24 requirement.

By combining information from field inspections of HVAC systems and 4-week monitoring of CO_2, this study identified some of the problems that cause classrooms to be under-ventilated. Our analysis shows that proper installation, operation, and maintenance of HVAC are all necessary in order to provide adequate ventilation in classrooms. All the HVAC systems in this study were recently installed, which suggests that replacing aging equipment with new equipment does not guarantee adequate ventilation in classrooms. More oversight on the installation and maintenance of equipment is needed. Requirements for commissioning HVAC systems, as required by California's Nonresidential Mechanical System Acceptance procedures in Title 24 [5], need to be enforced.

Monitoring CO_2 is one way for facilities staff to identify ventilation deficiencies. Schools with a central EMS can log CO_2 levels and set alerts when high levels are observed. With these data, inadequate ventilation

Table 4
Mean indoor air temperature measured in 103 classrooms.

Season	School	Number of Classrooms	Mean Temperature		
			<20 °C	20–23 °C	>23 °C
Cooling	1, 8–11	43	1	19	23
Shoulder	2, 7	24	–	1	23
Heating	3–6	36	2	19	15
Total	–	103	3	39	61

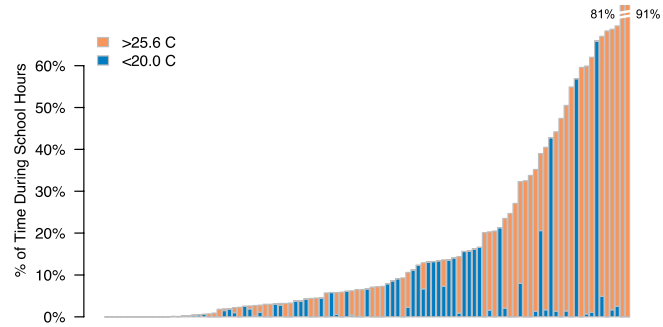

Fig. 6. Percent of time during school hours when measured indoor air temperature was either too cold (<20 °C) or too warm (>25.6 °C). Each bar represents a classroom. Data is missing from 1 classroom because of sensor problem.

could be detected more easily by facilities staff, who could then investigate the source of the problem. Displaying CO_2 concentrations on the thermostat so that the information is visible can also raise teachers' awareness. Access to data on CO_2 concentrations may be one reason why classrooms with DCV had higher ventilation rates; any problems with installation or maintenance of a DCV system would be immediately detectable because of the presence of the CO_2 sensor. While DCV may not be suitable or feasible for all classrooms, installing thermostats with CO_2 sensors is a solution that can enable the detection of ventilation problems in classrooms with any type of ventilation equipment. Another method to detect ventilation problems is periodic testing of ventilation systems and measurement of ventilation rates, however this method does not provide continuous real-time monitoring.

Analysis of indoor air temperature found that many classrooms were too warm for extended periods of time when occupied. Such conditions could result in thermal discomfort and impact student performance. More detailed analysis is needed to determine the cause(s) for classrooms operating outside of the expected temperature range, including consideration of the heating/cooling capacities of HVAC equipment, temperature setpoints, and level of control on thermostat settings by the teacher.

4.1. Limitations

Despite the effort to include a diverse range of characteristics when recruiting schools to participate in this study, the small number of schools (N = 11) and classrooms (N = 104) sampled may not reflect the distribution of conditions in classrooms that replace HVAC equipment, let alone the broader population of California K-12 schools. For example, classrooms in this study with DCV systems had adequate ventilation, but they also had full-time energy managers who were involved in the equipment installation and commissioning process, more so than other classrooms in the study. This suggests that the level of engagement by facilities staff may confound comparisons between different types of ventilation systems. Generalizations about the problems with ERVs, economizers, and poorly maintained filters observed in this study would require data that can represent California schools more broadly.

This study used the steady-state method to estimate VRs because it has been widely used in prior studies. Alternative methods to estimate VRs from CO_2 data, such as the decay method and the transient mass balance method [14], also have limitations and sources of uncertainties. The estimated VRs as a metric based on the daily highest 15-min CO_2 does not account for the other times when a classroom may be ventilated at a higher per-person rate. During the day, classrooms may have had variable VRs because of an economizer and/or DCV use. It is also possible that the highest CO_2 on many days could have been influenced by a higher student activity rate than assumed in the calculation of VRs; actual CO_2 emission rates from students vary depending on their

Table 5
Summary of ventilation rate and CO_2 concentration in US schools as reported in the literature.

Reference	Location and Grade Levels	Number of Classrooms (CR)/Schools (S)	CO_2 Concentration (ppm)		Ventilation Rate (L/s-person)
			Daily Average	Daily Peak	
This study	CA K-12	CR = 94 S = 11	Mean = 895 Median = 897	Mean = 1353 Median = 1375	Mean = 5.2 Median = 4.8
[6]	CA Grade 3-5	CR = 71	–	Mean = 2370 Median = 2280	Mean = 3.5 Median = 2.8
[11]	US Southwest Grade 5	CR = 104 S = 104	–	–	Mean = 4.2
[18]	US Grade 5	CR = 54 S = 54	–	–	Mean = 3.9
[19]	MI Elementary, Middle	CR = 47 S = 30	Median = 750	–	–
[20]	NY K-12	CR = 64 S = 10	Mean = 812	–	–
[21]	ID, WA Elementary	CR = 434 S = 22	ID Mean = 1240 WA Mean = 980	–	–
[22]	TX Elementary	CR = 385 S = 60	Mean = 1672	–	–
[23]	OK Grade 3	CR = 26 S = 12	Mean = 1028 Median = 978	Mean = 1542 Median = 1456	–
[24]	IA, NB K-12	CR = 220	Mean = 1171	–	Mean = 5.6

physical activity level prior to entering the classroom. More detail data collection on daily student attendance during each class period would support calculations using the transient mass balance method to provide alternative estimates of VRs.

Due to limited time, field inspections were mostly observation-based. Outdoor air flow rates were measured using a flow hood only in a subset of the classrooms. Additional equipment and/or installation problems may be identified from more detail field characterization of the HVAC system. Monitoring of HVAC system operation during the study period, for example, would likely provide useful data to better characterize the problem of under-ventilation in some classrooms.

5. Conclusion

Overall, classrooms with recent HVAC retrofits had higher VRs than reported generally in the literature, including in a recent California study. However, the VRs of many classrooms were still below the requirements of the ASHRAE 62.1 standard or California's Title 24. Among the studied classrooms from 11 schools in California, wall-mount systems commonly used in portable classrooms had higher CO_2 concentrations and lower estimated VRs compared to rooftop units. Classrooms with economizers, with and without DCV, tended to have lower mean CO_2. But, measured CO_2 concentrations in the studied classrooms indicate that many were still under-ventilated compared to the minimum requirement. Inadequate ventilation was found in classrooms at all grade levels. Under-ventilation was caused by improperly selected equipment, lack of commissioning, incorrect fan control settings ("auto" mode only providing ventilation when HVAC was running in heating or cooling mode) and maintenance issues (heavily loaded filters due for change or past service life).

We recommend better oversight to ensure the right HVAC equipment is purchased and installed properly in classrooms. The HVAC system must be configured to continuously provide outdoor air when the classroom is occupied regardless of heating or cooling needs. Finally, it is important to provide routine filter maintenance. Periodic testing of ventilation systems and/or continuous real-time CO_2 monitoring (either by stand-alone monitors or incorporated into thermostats) is recommended to enable the detection and correction of ventilation problems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.106426.

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