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Investigating dilution ventilation control strategies in a modern U.S. school bus in the context of the COVID-19 pandemic

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Abstract

Fresh air ventilation has been identified as a widely accepted engineering control effective at diluting air contaminants in enclosed environments. The goal of this study was to evaluate the effects of selected ventilation measures on air change rates in school buses. Air changes per hour (ACH) of outside air were measured using a well-established carbon dioxide (CO_2) tracer gas decay method. Ventilation was assessed while stationary and while traversing standardized route during late autumn/winter months in Colorado. Seven CO_2 sensors located at the driver's seat and at passenger seats in the front, middle, and rear of the bus yielded similar and consistent measurements. Buses exhibited little air exchange in the absence of ventilation (ACH = 0.13 when stationary; ACH = 1.85 when mobile). Operating the windshield defroster to introduce fresh outside air increased ACH by approximately 0.5–1 ACH during mobile and stationary phases. During the mobile phase (average speed of 23 miles per hour (mph)), the combination of the defroster and two open ceiling hatches (with a powered fan on the rear hatch) yielded an ACH of approximately 9.3 ACH. A mobile phase ACH of 12.4 was achieved by the combination of the defroster, ceiling hatches, and six passenger windows open 2 inches in the middle area of the bus. A maximum mobile phase ACH of 22.1 was observed by using the defroster, open ceiling hatches, driver window open 4 inches, and every other passenger window open 2 inches. For reference, ACHs recommended in patient care settings where patients are being treated for airborne infectious diseases range from 6 to ≥12 ACHs. The results indicate that practical ventilation protocols on school buses can achieve air change rates thought to be capable of reducing airborne viral transmission to the bus driver and student passengers during the COVID-19 pandemic.

Keywords

Air change rate; COVID-19; infection transmission; school bus; tracer gas

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Introduction

Approximately 26 million children are transported daily on approximately 480,000 school buses in the United States (U.S.) (NSTA 2013; Abulhassan and Davis 2021). Types A and B school buses are shorter, often built on a cutaway van or front-section vehicle chassis, and typically carry fewer passengers compared to types C ("conventional") and D ("transit-style") school buses commonly used in the United States, which are larger and have higher occupancy capacity (e.g., 78 passengers).Tightly enclosed spaces such as buses may be conducive to the transmission of airborne infectious viruses. SARS-CoV-2, the virus that causes COVID-19, is a respiratory virus that can transmit person-to-person through droplets, aerosols, and direct contact, but apparently less so by fomite transmissions based on current but evolving evidence (Allen and Marr 2020; Cai et al. 2020; Morawska and Milton 2020; Tang et al. 2020; Meyerowitz et al. 2021; Rabaan et al. 2021; CDC NCIRD 2021a).

Nationwide, U.S. school districts contend with the myriad challenges of continuing to transport and educate children as safe as reasonably practicable using a variety of controls to mitigate SARS-CoV-2 infections including physical distancing, the use of face coverings (i.e., "masks"), and enhanced cleaning and disinfection protocols both in classrooms and during vehicle (i.e., bus) transport of students (Abulhassan and Davis 2021). In 2020, at least six Colorado school districts reported outbreaks of COVID-19 among bus transportation employees (Robles 2020).

An outbreak of COVID-19 on a motorcoach bus was confirmed in Zhejiang province of China in January 2020 (Shen et al. 2020). This cohort study investigated COVID-19 infections in adult passengers riding in one of two similarly designed buses traveling to a worship event on the same day and route duration with the index patient. Passengers on the bus with the index patient reportedly had a 34.3% higher risk of getting COVID-19 than persons on the other bus, and all passengers, including the index patient, participated in the same worship event and ate at a luncheon at the destination. While exposure to SARS-CoV-2 was likely not limited to being on the bus (a luncheon and worship event occurred), the authors concluded airborne spread of SARS-CoV-2 in the enclosed, recirculated air environment of the bus with the index patient was the most likely explanation for the higher transmission rate among passengers on the same bus as the index patient.

The use of dilution ventilation as an engineering control is widely accepted to be effective to dilute air contaminants in workplace environments (Burgess et al. 2004). Recent research endorses the use of effective dilution ventilation measures (i.e., increasing outdoor air change rates) as a key element in limiting the spread of SARS-CoV-2 (Morawska et al. 2020). Improved ventilation measures specifically help to reduce the concentration of viral particles potentially found in indoor enclosed spaces, reducing the overall viral dose to individuals with those spaces. As such, the Centers for Disease Control and Prevention (CDC) has included ventilation improvements as one component of a layered approach including physical distancing, wearing face masks, hand hygiene, and vaccination (including boosters) to reduce exposures/infection risks for SARS-CoV-2 (CDC NCIRD 2021c). Multiple organizations, including ASHRAE, have provided critical guidance and recommendations for improved ventilation measures in occupied buildings (Schoen

2020). However, detailed guidance for certain other enclosed non-building spaces such as school buses is lacking. To the authors' knowledge, investigation of the use of dilution ventilation has not been studied in the context of the COVID-19 pandemic and school bus transportation.

Unlike other high-capacity tightly enclosed forms of transportation (e.g., commercial passenger aircraft) designed and engineered to provide laminar airflow directed downward from ceiling to floor along with high efficiency filtration and outside air change rates more than 12–15 air changes per hour (ACH), school buses are configured with comparatively simple active (mechanical) and passive (windows and ceiling hatches) ventilation (Khatib et al. 2020).

Active ventilation systems in school buses without air conditioning typically consist of an outside air intake connected to a mechanical fan unit to supply coarsely filtered air for windshield defrosting and general ventilation. Multi-speed radial bladed fans are also mounted on the headboard near the windshield to enhance defrosting of the large windshield. These fans can move and distribute air short distances and aid in air mixing toward the front of the bus but do not bring outside air into the bus. Passive ventilation typically consists of two ceiling-mounted hatches (also intended for escape in the event of a crash/side roll-over) with the rear hatch having an operable fan incorporated into the hatch (Figure 1), and 12–13 openable windows on each side of a Type C or D bus. A sliding window is typically located to the left of the driver. Depending on the amount of active and passive ventilation and air mixing in a school bus, exposure risks to potentially infectious aerosols (e.g., SARS-CoV-2) will vary based on the source strength of contagious individuals, occupant density, and the air change rate in the bus.

The goal of this study was to measure dilution ventilation and air change rates in typical school buses to identify practical strategies to increase ventilation and achieve desired air change rates.

Air change rates, often expressed as air changes per hour (ACHs) of outside air, are a measure of how many times a volume of air is changed over (added or removed) in a space in an hour. ACHs in buildings are often measured by multiplying the volumetric flow rate of supply air (in cubic feet per minute [CFM]) by 60, then dividing by the volume of the space and multiplying by the percentage of outside air delivered by the ventilation system. Additionally, ACHs in an occupied space can be determined through tracer gas decay methods without the need to directly measure volumetric flow rate or percentage of outside air. ACHs recommended in patient care settings where patients are being treated for airborne infectious diseases range from 6 to ≥12 ACHs. By introducing elevated concentrations of carbon dioxide (CO_2) into a minimally populated bus (three adults including the driver) and then measuring its decay during simulated 10- and 20-min school bus routes, we assessed how reasonable combinations of active ventilation, open windows, and hatches influenced ACH in the bus.

Methods

The investigators partnered with a large school district outside of Denver, Colorado and were granted access to three International Truck and Engine Corporation (IC) 77–passenger general education and mountain buses (model PB10500, 2020–21 vintage), nearly identical in configuration.

The study was conducted in two parts (stationary and mobile phases) over a period of 5 days in September/November 2020 and January/February 2021. The stationary phase was performed with the school bus parked in the fleet maintenance garage. The mobile phase was performed as the buses were driven on a standardized and representative school bus routes of 6.5 and 3.7 miles, beginning and ending at an elementary school, and requiring 20 and 10 min to complete, respectively. The typical speed for the routes was approximately 23 miles per hr (mph). Stops of approximately 5–10 sec were designed into the routes (including opening the door) to simulate boarding/disembarking, specifically three stops for the 6.5-mile route and one for the 3.7-mile route. The buses were operated by a school district employee licensed to drive and operate the bus. During the mobile phase of the study, occupants in the bus included two researchers and a school district driver. No students were aboard the buses at any time.

Specific ventilation variables investigated included (a) operating the fresh air windshield defroster system fans and two headboard-mounted air circulation/mixing fans on low and high speeds, (b) opening or closing two ceiling-mounted hatches while operating the powered fan for the rear hatch, and (c) opening or closing to varying degrees the vertical sliding passenger windows on the sides of the bus as well as the driver’s horizontal sliding window. Table 1 describes the controls and their settings that were evaluated in this investigation.

For the stationary component, ventilation variables studied ranged from completely quiescent conditions with no active or passive ventilation to maximum active and passive ventilation (Table 2), conducted sequentially in an order judged *a priori* to offer the least to most ventilation. For the mobile phase, both a serial and randomized approach was used to assess combinations of ventilation conditions (Table 3). Multiple trials of four of the different ventilation conditions (shown in Table 3 as conditions #1, 3, 8, 9, and 13) were evaluated during the mobile phase to evaluate variability of results across these trials. The underseat heaters were operating during conditions 1, 3, 9, and 13. To test the effect of the heaters, one additional condition was added (condition #8 in Table 3), with the same variables as condition #9 except with the underseat heaters turned off. Randomization of the order in which ventilation variables were assessed for the mobile trials ensured that all tests for a single condition were varied and not performed at any one time of day due to the anticipated changes in weather conditions, including ambient temperature.

To evaluate the effect of selected ventilation variables, air change rates were measured using a well-established CO_2 tracer gas decay method (ASTM Standard E741–11 2017; ASTM Standard D6245–18 2018). For each trial, food-grade CO_2 gas was released inside the stationary bus, with all doors, windows, and hatches closed. To facilitate uniform gas distribution, the CO_2 was released through the bus using a perforated ¼-inch Tygon tubing running the length of the passenger seating in the bus, taped in place onto the top of the bench seats. The use of a battery-powered leaf blower or a box fan aided gas mixing and distribution in the enclosed bus. CO_2 concentrations were measured at 1-sec intervals using seven TSI Q-TRAK Model 7565 indoor air quality monitors configured with a TSI model 982 probe with electro-chemical sensor (TSI, Inc., Shoreview, MN). The instrument can measure and log CO_2, temperature, and relative humidity. The measurement range for CO_2 is 0–5,000 parts per million (ppm) with an accuracy of ±3% of instrument reading or ±50 ppm (TSI 2008). The sensing probes for each instrument were secured to the top of a bench seat at one of seven locations in the bus: at the driver's seat and on the left and right side of three rows in the front, middle, and rear of the bus, approximately 49 inches above the bus floor. The CO_2 was released until concentrations throughout the bus stabilized at approximately 4,800–5,000 ppm after which each trial testing the ventilation variables in question was initiated. (Note: Occupational Safety and Health Administration's (OSHA's) permissible exposure limit (PEL) for CO_2 as an 8-hr time-weighted average is 5,000 ppm, with a National Institute for Occupational Safety and Health (NIOSH) short-term exposure limit (STEL) of 30,000 ppm or 3%) (NIOSH 1997).

The air change rate was calculated at each location consistent with ASTM E741–11 (ASTM Standard E741–11 2017). Each trial was analyzed independently using simple linear regression. The simple linear regression analyzed the natural log of the CO_2 concentration measurements (dependent variable) as a function of time measured in hours (independent variable) for each trial and location. Each regression model included CO_2 concentrations starting from the time of stabilization (and route start for mobile trials) and ending at the time when concentrations reached 800 ppm. This lower limit was chosen to minimize the effect of ambient CO_2 and that generated by observers and the driver on the bus. To obtain an average air change rate for each trial, all location measurements were included within a single regression model. The resulting slope and coefficient of determination (R^2) from each regression model are reported. To test differences in the air change rate between locations within each trial, an interaction term for time of measurement (in hours) by location was added to each trial regression model. The p-value for the interaction term is reported.

For conditions that were repeated during multiple trials, an average air change rate for the condition was calculated using a simple linear regression of the natural log of the CO_2 concentration measurements as a function of time measured in hours pooled for each condition. To assess if there were any statistically significant differences between the conditions that were observed multiple times, a linear mixed regression model of the natural log of the CO_2 concentration measurements as a function of time measured in hours and a condition by time measured in hours interaction term was used. The random terms in the linear mixed regression model included a random intercept and a random slope for each trial. To assess which conditions differed, pairwise comparisons were made. All analyses were done in SAS version 9.4 (Cary, NC).

This activity was reviewed by CDC and was conducted consistent with applicable federal law and CDC policy (see, e.g., 45 C.F.R. part 46; 21 C.F.R. part 56; 42 U.S.C. §241(d), 5 U.S.C. §552a, 44 U.S.C. §3501 et seq.).

Results

Stationary testing

Twelve different experimental conditions comprising 15 individual tests were performed when the bus was stationary. Ambient temperature range in the bus while parked in the maintenance garage during tests was 71–74 °F. Results are described and listed serially in Table 2 as they were conducted. Air change rates were in a range of 0.13 ACH (completely enclosed conditions) to 11.4 ACH. The highest ACH was obtained from simultaneous use of full active ventilation, all windows, and escape hatches open and the rear hatch fan operating. The closed bus had a very low (0.13) air change rate. Operating the defroster on fresh air mode with high fan speed increased ACH to 1.0 ACH, nearly an order of magnitude. Opening the ceiling escape hatches and operating the rear hatch fan resulted in 1.8 ACH. Based on the incremental increase observed with each condition, to approach 6 ACH in a stationary bus it is likely that all windows need to be at least half open, ceiling hatches fully open with fan on, and the defrost fan on high.

Air change rates measured at each of the seven locations in the bus were typically within about 7% (median percent difference 7.3%, data not shown) though the variation was somewhat larger for experimental conditions involving fully open windows (average percent differences ranging from 14–29%). This suggests that, under most conditions, effective mixing of CO_2 was achieved and similar ACH occurred at different locations in the bus. Slopes of overall CO_2 decay curves were highly correlated (average $R^2 = 0.87$) yielding a consistent log/linear straight line fit for the CO_2 decay. Reproducibility can be seen in Table 2 in condition #12 which was repeated three times with comparable results in a range of 10–11.4 ACH.

Mobile testing

A total of 31 mobile tests comprising 16 different conditions were performed, with results ranging from 1.8–22.1 ACH presented in Table 3. Ambient outdoor temperature ranged from 24–39 °F on January 19 and 23–44 °F on February 24. When the bus was mobile, with defroster and fans off and all hatches and windows completely closed (conditions #1 and 2, Table 3), we measured 1.8–1.9 ACH, with outside air likely entering the bus through gaps and seals around door and windows. Small differences were observed in air change rates (2.4 vs. 2.7 ACH) when running the front windshield defroster fan on low versus high (conditions #4 and 6, Table 3). Likewise, little difference was seen in air change rates (2.5 vs. 2.7 ACH) when air mixing fans near the front windshield were on high versus off (conditions #5 and 6, Table 3), but did result in perceptible increased noise levels in the bus which may be perceived as annoying or distracting to the driver. While intended to maintain passenger comfort, the use of underseat heaters did not appreciably affect air change rates during the mobile testing as they recirculate but do not introduce outside air (conditions #3 and 4, and conditions #8 and 9, Table 3).

A notable increase in ACH occurred when the front and rear ceiling hatches were opened and the rear hatch fan was turned on (conditions #7 and 10, Table 3). Opening the ceiling hatches and operating the hatch fan can be an important factor for increasing the air change rate in the bus, as this variable alone resulted in air change rates consistently exceeding 6 ACH during mobile tests. Fully opening the ceiling hatch parallel to the roof (Figure 1) resulted in a higher air change rate of 8.2 ACH (condition #10, Table 3) compared to operating with the hatch opened but tilted back in a “scooping” position (Figure 2) which resulted in 6.5 ACH (condition #7, Table 3) though additional testing would be needed to verify this difference.

Increasingly more ACH were measured when additional variables were introduced such as the defroster fan and windows open to varying degrees. Operating the fresh air defroster on low with open hatches and the hatch fan operating resulted in air change rates exceeding 9 ACH (condition #9, Table 3). Opening six windows 2 inches each, in addition to the fresh air defroster, open ceiling hatches, and hatch fan operating, further increased ACH to above 11 (condition #13, Table 3). Average temperatures in the bus remained above 60 °F during testing with open hatches and six windows open 2 inches on a sunny day with outside temperatures of 35 °F, even without the heat contribution of passengers.

An impact on ACH from opening the driver’s window 4 inches was observed. In addition to using the defroster, mixing fans, and open ceiling hatches, opening the driver’s window markedly increased bus ACH from 7.6 to 11.0 (conditions #11 vs 12). However, with the further addition of six open passenger windows, opening the driver’s window (conditions #14 vs. 15) created a minor increase in ACH from 12.1 to 13.2.

Comparing the conditions for which multiple trials were performed, we found no significant difference ($p = 0.39$) in air change rates in the fully closed bus (Table 3, condition #1, 1.9 ACH) compared to operating the bus with only the defroster on low (Table 3, condition #3, 2.2 ACH). Similarly, there was also no difference ($p = 0.90$) between operating the bus with the underseat heaters on (Table 3, condition #9, 9.4 ACH) compared to the underseat heaters off (Table 3, condition #8, 9.1 ACH). The air change rate achieved by the combination of operating the fresh air defroster on low, opening ceiling hatches with hatch fan on, and opening six passenger windows 2 inches, (Table 3, condition #13, mean ACH = 12.4) was significantly higher than other operating conditions ($p < 0.001$ vs. conditions #1, 3, 8, and 9).

Similar to stationary testing, air change rates measured at each of the seven locations were remarkably consistent, typically within about 6% (median percent difference 5.7%, data not shown) and in contrast with stationary testing remained consistent even when windows were fully opened (average percent differences 8.7%). Slopes of overall CO_2 decay curves were again highly correlated (average $R^2 = 0.92$) yielding a consistent log/linear straight line fit for the CO_2 decay.

Discussion

There is an increasing awareness of the importance of ventilation for decreasing the risk of SARS-CoV-2 transmission (ASHRAE 2020). It is thus important to characterize ventilation rates on school buses to help school districts develop practical protocols to reduce the risk of transmission of SARS-CoV-2 and other respiratory viruses to help protect school bus drivers, monitors, and other school staff who may be at higher risk of COVID-19 and respiratory disease morbidity. As shown by results in this study, implementing practical changes using the bus defroster ventilation system, windows, and hatches can achieve air change rates that provide considerable dilution ventilation to aid in minimizing risk. Furthermore, our experience suggests that air change rates exceeding 6 ACH can be maintained in relatively cold conditions (> 32 °F) using defrosters and open ceiling hatches while simultaneously maintaining comfortable conditions (50 °F) for passengers wearing cool weather clothing.

Formal guidance from public health agencies regarding recommended minimum ACH for infection control for school buses is limited. In almost all settings, there is a lack of controlled interventional studies that quantify the relative infection control performance of specific outside or filtered air ventilation rates (English and Koenigshofer 2015). Understanding ACH is useful in recognizing how much dilution ventilation or “fresh air” is supplied to a space to dilute air contaminants or odors that may be in the space. In the case of the current pandemic, SARS-CoV-2 respiratory droplets and aerosols can be released into the air of a space such as a school bus when infected individuals breathe, talk, cough, sneeze, or sing. Depending on air movement and dilution ventilation, droplets, and aerosols can remain airborne for minutes to hours (CDC NCIRD 2021b). The use of dilution ventilation in indoor or enclosed spaces is desirable to mitigate transmission of COVID-19. While 10–13 ACH provides the most exposure reduction, our data show that increasing ventilation to at least 6–9 ACH in a moving school bus is relatively easy to achieve.

For airborne infection isolation rooms (AIIR) in hospitals or clinics where patients are treated for airborne infectious diseases, CDC-recommended ventilation design criteria are a minimum 6 ACH for existing hospitals or clinic facilities and ≥12 ACH for areas under renovation or for new construction (CDC NCEZID 2003). Similarly, ASHRAE has recommended provision of ≥6 ACH with 100% outside air, in combination with high-efficiency particulate air (HEPA) filtration and ultraviolet germicidal irradiation (UVGI) in patient rooms in healthcare facilities (ASHRAE 2020). However, enhanced indoor ventilation has not obviated the concurrent use of source control (masks) as an important component of infection control, especially in school environments (Foster and Kinzel 2021; Schibuola and Tambani 2021).

Our study determined that closed school buses had very low air change rates ranging from just 0.13 ACH when stationary, to about 1.9 ACH when moving. The range of air change rates of 1.8–2.7 ACH reported in this study under closed conditions with and without active ventilation (i.e., defroster system) are within the ranges reported by others. Rim et al. (2008) reported a range of 2.6–4.5 ACH for six closed school buses (international diesel engines, but of varying ages, mileage, and operational air conditioning systems) during actual routes in Texas, and Chaudhry and Elumalai (2020) reported a range of 2.2–6.7 ACH for 14 closed school buses (Tata manufactured, but of varying models, size, mileage, and model year) during actual routes in India. Our results for hatches and/or windows open when moving (6.5–13.7 ACH) are also well within the range of 4.8–14.9 ACH reported by Chaudhry and Elumalai (2020) for Indian school buses with windows open.

Predictably, and as our study demonstrated, opening windows increases ventilation in school buses. However, we were unable to study multiple open window configurations. A 2017 study of airflow patterns inside a Type C school bus using computational fluid dynamics modeling reported on the effects of opening four different configurations of side windows (and the driver's window) at speeds of 20, 40, and 60 mph (Li et al. 2017). The study did not consider active ventilation. Predictably, the authors reported that higher bus speeds resulted in higher ventilation rates (Li et al. 2017). The authors reported that opening the driver's window allowed engine exhaust infiltration into the bus, but opening windows in the middle of the bus prevented that. The authors reported that the lowest relative air pressure was observed at the driver's window, and highest relative pressures were observed toward the middle windows of the bus and suggested those two window locations have greatest impact on airflow patterns and ventilation rates inside the bus. The authors advised always opening the middle windows when the driver's window is open and not opening the driver's window alone. They further noted that the freshest air in the bus likely enters through the middle sections of windows and gaps in seals in the bus. In support of this, we also observed that opening the driver's window when six middle windows are each open 2 inches yields only a minor increase in ventilation to the driver and the bus overall.

Strengths and limitations

In this study, ventilation and ACHs were investigated under a wide variety of passive and active ventilation conditions in modern conventional school buses. Although the effects of dilution ventilation were in three different buses of the same make, model, and vintage, the authors feel it is reasonable to expect that analogous dilution ventilation effects may occur in other sizes, makes, and models of school buses based on this and other literature.

Students were not aboard the bus during our study, and we do not know if the presence of passengers would alter study findings in a significant way. The range of environmental conditions (e.g., temperature, sunlight, ambient wind velocity) and bus road speeds present at the time of the study measurements were relatively stable, and the relative impact of variation in these variables on quantitative changes ACH is uncertain. Some bus routes will be longer than the durations investigated in this study. Irrespective of air change rates, longer periods of occupancy in the relatively confined space of a school bus can (depending on occupancy numbers and infectious persons) increases the risk of exposures to potentially infectious aerosols.

Conclusions

This study provides evidence that implementation of the readily available passive and active ventilation measures investigated may greatly increase average ACH inside school buses. The use of dilution ventilation in the form of active and passive engineering controls to increase ACH is desirable in occupied spaces such as a school bus as part of a layered approach of infection prevention controls (e.g., use of masks for source control, social and physical distancing, surface cleaning and decontamination, frequent handwashing and use of alcohol-based hand sanitizers) and can help to limit exposure to and transmission of the SARS-CoV-2 virus during the pandemic.

Recommendations

Based on study results, implementing the following minimum practices, which resulted in notable increases in dilution ventilation and ACHs above 6, are advised:

- Operate buses with the ceiling hatches open and activate hatch fans (if present) to increase ACH, weather permitting. It is preferable to orient the hatches flat and pushed completely open; tilting the hatches forward or backward did not increase ACH in this study.
- Use the fresh air defroster fan system to bring in outside air; the high-speed option is preferred provided fan noise is not distracting to the driver

For further risk minimization when weather permits, opening windows on both sides of rows in the front, middle, and back of the bus (e.g., row 3, 8, and 11) to the first stop (a 2-inch opening) can achieve several additional ACHs. All trials with the addition of this open window configuration achieved at or above 12 ACHs during mobile testing.

Additionally, school districts are advised to inform and educate school bus drivers on why ventilation measures should be implemented with appropriate considerations of seasonal and environmental conditions (e.g., community air pollution events and alerts). This includes include developing school policies that identify specific controls that can be used to improve bus ventilation. Additionally, school districts are advised to educate school bus drivers of such policies and empower them to implement them on their buses.

This activity was reviewed by CDC and was conducted consistent with applicable federal law and CDC policy (see, e.g., 45 C.F.R. part 46; 21 C.F.R. part 56; 42 U.S.C. §241(d), 5 U.S.C. §552a, 44 U.S.C. §3501 et seq.).

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Figure 1.

Photo of ceiling hatch fully opened, with the hatch fan on. Passenger windows are closed. A CO_2 probe attached to the back of the bench seat can be seen in the rear of the bus.

Figure 2.
"Scooped" configuration of the ceiling hatch, with only the distant side of the hatch tilted upwards.

Table 1.

Bus controls evaluated to change ventilation or heating.

Control	Available settings	Description
Defroster	High and low blower speeds. Fresh air and recirculate settings	Single blower motor with driver operated controls provides dedicated filtered air from an intake on driver’s side of bus hood. The defroster controls allow for 100% fresh air from the exterior course filtered intake, 100% recirculated air, or a mixture of fresh and recirculated air.
Mixing fans	High and low fan speeds	Two axial fans mounted on the front headrail of the bus. Typically used to increase efficiency of defroster to deice or defog the windshield. Provided recirculating air only.
Roof hatches	Three settings for opening: pushed completely up parallel to the roof, back of hatch pushed up (i.e., tilted forward), or front of hatch pushed up (i.e., tilted back or scooped). Powered fan on or off on rear hatch only.	Two openable hatches in the middle and rear of the bus. Rear hatch had a powered fan (Figure 1).
Underseat heaters	High and low blower speeds	Heaters consisted of a heating coil and dual blower motors located under passenger seats, toward the rear of the bus. These heaters recirculate air filtered through a coarse metal screen and did not have outside air intakes.
Driver window	Continuously adjustable horizontal sliding window	Openable window next to the driver.
Passenger windows	Adjustable in 2-inch increments	Passenger window located adjacent to each passenger bench. Each bus had 26 passenger windows.

Table 2.

Summary of stationary test results, November 23–24, 2020[a].

Condition	Defrost	Mixing fans	Hatches	Driver window	Passenger windows	# of Tests	Air Changes (ACH) Average (Range)
1	Off	Off	Closed	Closed	Closed	1	0.13
2	Off	Off	Closed	Closed	6 windows open 2 inches (rows 3, 8, 11)	1	0.4
3	Off	Off	Open, Fan off	Closed	Closed	1	0.5
4	High, Fresh	High	Closed	Closed	Closed	1	1.0
5	High, Fresh	High	Closed	Closed	6 windows open 2 inches (rows 3, 8, 11)	1	1.5
6	Off	Off	Open, Fan on	Closed	Closed	1	1.8
7	Off	Off	Open, Fan on	Closed	6 windows open 2 inches (rows 3, 8, 11)	1	1.8
8	High, Fresh	High	Open, Fan on	Closed	6 windows open 2 inches (rows 3, 8, 11)	2	2.2 (2.1–2.4)
9	High, Fresh	High	Open, Fan on	Open 4”	6 windows open 2 inches (rows 3, 8, 11)	1	3.6
10	High, Fresh	High	Open, Fan on	Open 4”	12 windows open 2 inches (every other window)	1	4.3
11	High, Fresh	High	Open, Fan on	Open 4”	26 windows open 2 inches (every window)	1	4.7
12	High, Fresh	High	Open, Fan on	Fully Open	26 windows fully open (every window)	3	10.8 (10.0–11.4)

[a] Underseat heaters off for all trials.

Color Scale:

Table 3.

Summary of mobile test results, January 19 and February 24, 2021.

Condition	Under seat heaters	Defrost	Mixing Fans	Hatches	Driver Window	Passenger Windows	# of Tests	Air Changes (ACH) Average (Range)
1	On	Off	Off	Closed	Closed	Closed	4	1.9 (1.8–1.9)
2	Off	Off	Off	Closed	Closed	Closed	1	1.9
3	On	Low, Fresh	Off	Closed	Closed	Closed	4	2.2 (2.1–2.3)
4	Off	Low, Fresh	Off	Closed	Closed	Closed	1	2.4
5	Off	High, Fresh	High	Closed	Closed	Closed	1	2.5
6	Off	High, Fresh	Off	Closed	Closed	Closed	1	2.7
7	Off	Off	Off	Open scoop, Fan on[a]	Closed	Closed	1	6.5
8	Off	Low, Fresh	Off	Open, Fan on[b]	Closed	Closed	4	9.3 (8.5–9.9)
9	On	Low, Fresh	Off	Open, Fan on[b]	Closed	Closed	4	9.4 (9.2–9.7)
10	Off	Off	Off	Open, Fan on[b]	Closed	Closed	1	8.2
11	Off	High, Fresh	High	Open scoop, Fan on[a]	Closed	Closed	1	7.6
12	Off	High, Fresh	High	Open scoop, Fan on[a]	Open 4”	Closed	1	11.0
13	On	Low, Fresh	Off	Open, Fan on[b]	Closed	6 windows open 2 inches (rows 3, 8, 11)	4	12.4 (11.5–13.7)
14	Off	High, Fresh	High	Open scoop, Fan on[a]	Closed	6 windows open 2 inches (rows 3, 8, 11)	1	12.1
15	Off	High, Fresh	High	Open scoop, Fan on[a]	Open 4”	6 windows open 2 inches (rows 3, 8, 11)	1	13.2
16	Off	High, Fresh	High	Open scoop, Fan on[a]	Open 4”	12 windows open 2 inches (every other window)	1	22.1

[a] Front hatch open with front of hatch tilted up; back hatch open with back of hatch tilted up; fan on high.

[b] Front hatch fully open, no tilt; back hatch fully open, no tilt; fan on high.

Color Scale: