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The impact of particle filtration on indoor air quality in a classroom near a highway

Abstract A pilot study was performed to investigate whether the application of a new mechanical ventilation system with a fine F8 (MERV14) filter could improve indoor air quality in a high school near the Amsterdam ring road. PM10, PM2.5, and black carbon (BC) concentrations were measured continuously inside an occupied intervention classroom and outside the school during three sampling periods in the winter of 2013/2014. Initially, 3 weeks of baseline measurements were performed, with the existing ventilation system and normal ventilation habits. Next, an intervention study was performed. A new ventilation system was installed in the classroom, and measurements were performed during 8 school weeks, in alternating 2-week periods with and without the filter in the ventilation system under otherwise identical ventilation conditions. Indoor/outdoor ratios measured during the weeks with filter were compared with those measured without filter to evaluate the ability of the F8 filter to improve indoor air quality. During teaching hours, the filter reduced BC exposure by, on average, 36%. For PM10 and PM2.5, a reduction of 34% and 30% was found, respectively. This implies that application of a fine filter can reduce the exposure of schoolchildren to traffic exhaust at hot spot locations by about one-third.

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Key words: Ventilation; Filtration; Particulate matter; Black carbon; Highway; School.

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Practical implications
Our results indicate that the application of a mechanical ventilation system with a fine filter can reduce classroom exposure to traffic exhaust at hot spot locations. However, filtration is only effective if the filters are frequently replaced and the ventilation system is properly maintained.

Introduction

Long-term exposure to traffic-related pollutants is associated with impaired lung growth, a higher prevalence of respiratory symptoms, and the onset of asthma in children (Gauderman et al., 2005, 2007; Janssen et al., 2003; McConnell et al., 2010). Detrimental impacts on cognitive development have been reported as well (Sunyer et al., 2015; Van Kempen et al., 2012).

Measurements of air pollutants near roadways consistently show elevated black carbon (BC) levels and other traffic-related indicators based on proximity. BC is a marker of gasoline, especially diesel exhaust (HEI, 2010), and consists mainly of particles in the submicron range (Riddle et al., 2008; Reche et al., 2014). Previous studies in the Netherlands have found an association between diesel exhaust and respiratory health effects in children (Brunekreef et al., 1997; Gehring et al., 2009; Janssen et al., 2003). Children are a particularly sensitive population subgroup to the health effects of air pollution. They inhale a proportionally larger dose of airborne particles compared with adults, due to their higher respiratory rates in general and higher breathing rates for physical activity (Bateson and Schwartz, 2008; Buonanno et al., 2011, 2012).

Outdoor particles are able to penetrate inside buildings, influencing indoor particle concentrations (Lin and Peng, 2010). Children spend a substantial part of their day at school, during daytime hours when traffic intensity is high. Therefore, the school environment is an important contributor to children's exposure to air pollutants (Mazaheri et al., 2014; Morawska et al., 2013). For this reason, minimizing the concentration of air pollution in classrooms is important.

Amsterdam is a densely populated city where many inhabitants reside, work, and attend school in direct proximity to major roadways. In 2010, a municipal regulation was adopted that prohibits the siting of new schools, day care centers, and homes for the elderly in proximity to highways (<300 meters) or along busy inner city roads (van Bergen, 2010). For political and practical reasons, it was decided that the regulation would only apply to new permit applications and that existing accommodation within the zones would not be relocated. This, however, raised questions from policymakers in Amsterdam, regarding potential mitigation measures to protect existing accommodation in proximity to busy roadways.

Several studies have reported that mechanical ventilation systems with air filtration could be effective in reducing levels of incoming particulate air pollution in homes and office buildings (Azimi et al., 2014; Bhangar et al., 2010; Fisk et al., 2000; MacIntosh et al., 2010; Stephens and Siegel, 2012). Fisk (2013) concluded in a recent review that particle filtration may help to reduce the substantial morbidity and mortality associated with indoor exposure to outdoor particles. However, only a few studies focused on classroom concentrations in occupied schools (McCarthy et al., 2013; Polidori et al., 2013).

In our study, we investigated whether the application of a new ventilation system with a fine F8 (MERV14) filter could be an effective mitigation measure in an occupied classroom in an existing older school building in close proximity to a highway, based on measurements of PM10, PM2.5, and BC.

Methods

The study was performed in a secondary school in close proximity to the A10-West ring road (figure 1).

The school was originally built in 1952, and the number of students (aged 12–18) has increased rapidly to around 600 in recent years. The school board wanted to build a larger school at its current location, but encountered the municipal regulation that prohibits the building of new schools within 300 meters of the highway. They approached our Department and requested air quality measurements to assess the current air quality. In addition, we evaluated the ability of a new ventilation system with a fine F8 (MERV14) filter to improve indoor air quality.

Study design

Particle concentrations were measured continuously inside an occupied classroom and outside the school during a 3-month study period in the winter of 2013/2014. The first 3 weeks of measurements were performed under baseline conditions with the school's existing mechanical ventilation system equipped with an old F5 (MERV10) filter.

During the fourth week, a new ventilation system (Unifan Octo 10, www.unifan.eu), equipped with an F8 (MERV14) filter was installed in the classroom by Unifan technicians. The classroom was not in use during this week. The previous ventilation system was switched off permanently.

Measurements to evaluate the effectiveness of the F8 filter were performed during the following 8 school weeks, in alternating 2-week periods with and without the F8 air filter in the ventilation system, but under otherwise identical ventilation conditions. Consequently, the study consists of three parts:

- Baseline study (sampling period 1)
- Intervention study: new ventilation system, no filter (sampling period 2)
- Intervention study: new ventilation system, with filter (sampling period 3)

The ability of the F8 filter to reduce exposure to particulate air pollution is based upon comparison of indoor/outdoor (I/O) ratios in sampling periods 2 and 3.

The baseline study (sampling period 1) was performed at the request of the school board and gives an impression of indoor air quality and indoor/outdoor relations under normal conditions.

Table S1 in the Supplementary Material presents a summary of the specific measurement weeks for the three sampling periods.

Throughout the entire study period, the teacher kept a daily diary with detailed information on the number of students, use of the ventilation system (only relevant

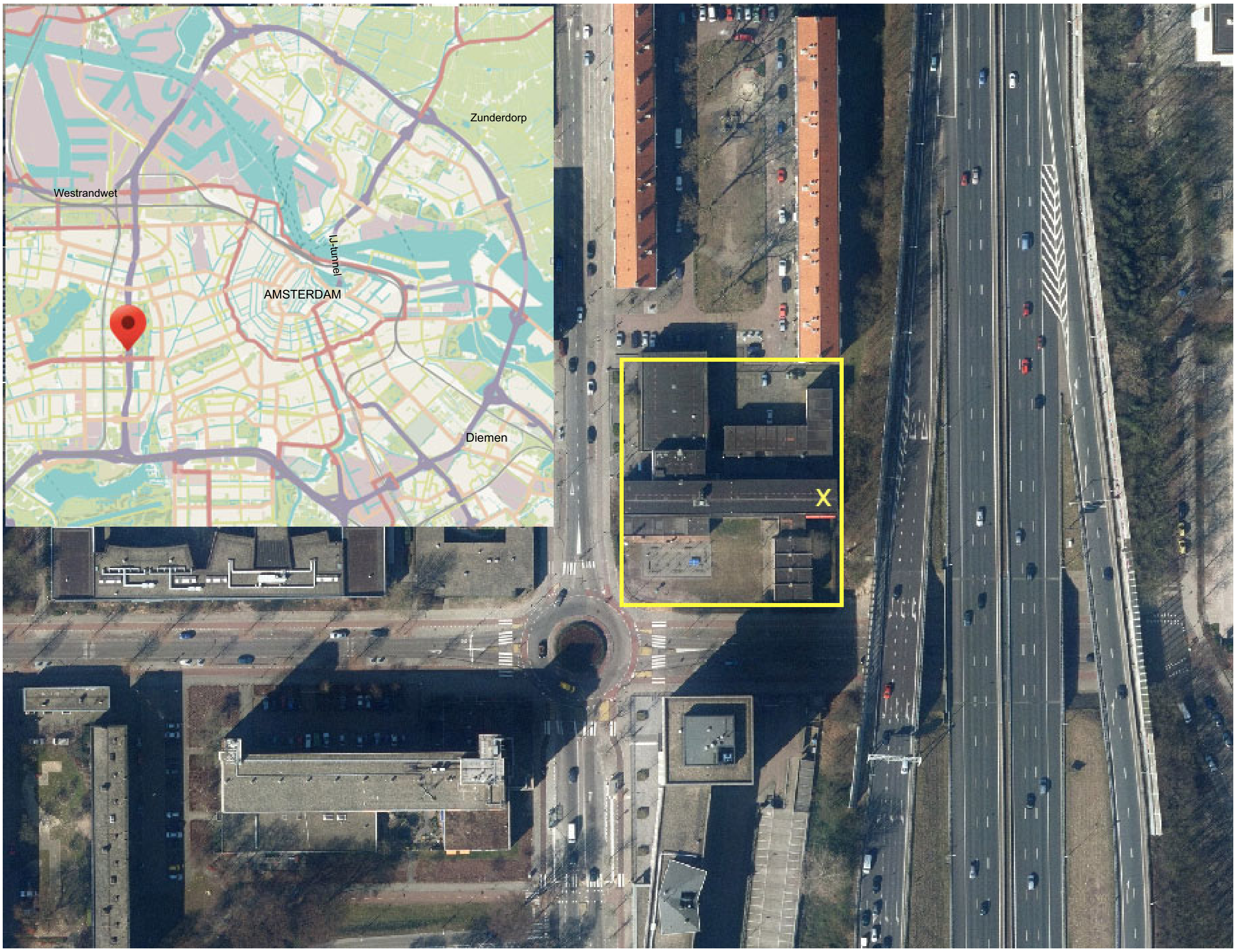

Fig. 1 Location of the school (red mark; yellow square) in Amsterdam (N 52 21.586, E 4 50.494) and intervention classroom (yellow cross). (Map copyright OpenStreetMap contributors www.openstreetmap.org/copyright, contains AND data, 2007 www.and.com)

Table 1 Characteristics of the highway and intervention classroom

Characteristic	
Total traffic intensity (including exit lanes)	146,500 vehicles/day
Total width of the freeway (including exit lanes)	68 m
Elevation of the freeway (above street level)	5 m
Height of the noise barrier (above freeway level)	4 m
Distance of study classroom to edge of freeway	20 m
Elevation of study classroom (floor) above freeway level	1 m
Height of study classroom	3.4 m
Floor area of study classroom	71 m^2
Volume of study classroom	241 m^3

during the baseline), noise nuisance, and perceived air quality.

Study site and classroom characteristics

Originally, the school - built before the highway was laid out - had only natural ventilation and was not designed with noise insulation and energy efficiency in mind. Several adaptations had been made to the classrooms since (double-glazed windows, mechanical ventilation).

The intervention classroom is situated on the top floor of the three-story building in the closest proximity to the elevated highway. This floor is located just above the highway but below the top of the glass noise barrier. The characteristics of the highway and the classroom are summarized in table 1.

The classroom has double-glazed windows on both sides, which cannot be opened, and ventilation louvers (openable) above the windows. It is located at the end of a hallway which has small, single-glazed windows that can be freely opened and closed during school hours.

The classroom was occupied each hour by different classes of students receiving geography lessons from the same teacher. The group size was registered hourly by the teacher and varied between 5 and 29 students. Teaching hours were from 8:30–10:30, 11:00–13:00, and 13:30–15:30 on all school days except Friday, when classes ended at 14:30. During morning break

(10:30–11:00) and lunch break (13:00–13:30), students leave the class. Each school day after teaching hours, the floor (wall-to-wall carpet) was vacuum cleaned, which was registered in the diary. The classroom was not affected by other indoor sources of particulate air pollution such as cooking or frying, as the school kitchen was located on the ground floor on the other side of the building. Eating or drinking in the class is prohibited at all times. There was no printer in the classroom, no blackboard (but a whiteboard), and no activities occurred that could otherwise affect the concentrations measured in the classroom (e.g., painting, etc.).

Measurements were performed during the same semester with the same teaching schedule and groups receiving lessons each week.

Ventilation during baseline and intervention

Baseline. An existing mechanical ventilation system with heat recovery and forced inlet and outlet was present in the school, installed separately for each classroom. Each classroom was able to regulate the output of the ventilation system separately. It was equipped with an F5 medium performance plate filter (MERV10), although the school board was not aware of this, as they had informed us before the start of the study that no air filtering was present. The school board is responsible for maintenance of the ventilation system and has a service and maintenance contract with an air technology company. Despite this, the F5 filter had not been replaced in a long time. It was located in a box that could not be fully opened. We were not able to identify the date of the last filter change as this was not registered. The baseline study was performed with the old F5 filter in the existing ventilation system, as this represents the normal ventilation situation in the classroom.

The inlet supply to the study classroom was located on the north side of the hallway. Incoming air was led through a duct just below the ceiling and crossed the hallway and a small storage room before it was led into the classroom through four supply grilles. The manually measured (FlowFinder mk2, ACIN instruments, Rijswijk, The Netherlands) supply airflow in the existing mechanical ventilation system was 126 m^3/h. Three exhaust grilles were located above the panels of the ceiling and were not accessible. Therefore, the exhaust airflow could not be measured with the instrumentation available.

The teacher recorded the use of the existing ventilation system and the hours that he switched it on and off in a daily diary. He was instructed not to change his normal ventilation habits during the baseline measurements. The ventilation louvers on the north side of the classroom were open during the baseline measurements. During classes, the existing ventilation system was switched off regularly (69% of time) due to the noise nuisance. It was always switched off after classes.

Intervention (new ventilation system). All ventilation louvers were closed before the start of the intervention period. A new ventilation system (Unifan Octo 10, www.unifan.eu) was installed with mechanical supply and extraction of air, equipped with an F8 filter, classified according to the European EN779 particle filter standard, and comparable to MERV14 according to ASHRAE 52.2 (Zhou and Shen, 2007). The ventilation system is equipped with heat recovery but not with air conditioning. Figure 2 presents a schematic overview of the new ventilation system.

A supply fan draws outdoor air, received from the rooftop, through a duct directly above the ceiling of the classroom. The supply air crosses a heat-recovery unit mounted in the back of the classroom, where it is heated by exhaust air that passes in a separate duct and is transported to the exhaust duct on the rooftop. The incoming outdoor air is filtered by an F8 (MERV14) multipocket, synthetic bag filter in a stainless steel frame. Pictures of the bag filter before installation and at the end of the sampling period are presented in the Supplementary Material.

The filtered air is brought into the classroom by means of a 3-meter-long micro-porous airbag, situated just below the ceiling. The air is removed through overpressure in the classroom and is also mechanically driven (fan). To protect the heat-recovery unit from dust, the exhaust air is filtered by an F7 (MERV13) filter before it enters the heat-recovery unit.

The purpose of our study was originally to test F9 filters (MERV15). This type of filter was explicitly ordered by the specialists from Unifan. However, an F8 (MERV14) filter was delivered and sold as F9 (MERV15) by the filter manufacturer. The technicians from Unifan were told that it was mistakenly labeled as an F8 filter, but had F9 properties. At the end of the study, the filter manufacturer admitted that they had indeed delivered F8 filters. Consequently, we have unintentionally performed the study with F8 filters instead of F9 filters. According to EN779, the minimum removal efficiency of 0.4-μm particles is 55% for F8 filters and 70% for F9 filters.

Originally, the Unifan Octo 10 system is CO_2 driven and designed to maintain a CO_2 concentration below 1000 ppm 98% of the time. For this study, it was set at a constant volume of supply air of 1000 m^3 per hour between 08:00 and 17:00 and 300 m^3 per hour during 17:00 and 08:00. Compared with the existing ventilation system (supply airflow 126 m^3 per hour), this is an eight-fold increase during the day. The exhaust air was set at 600 m^3 per hour between 08:00 and 17:00 and switched off after 17:00. Between 23 and 30 January 2014, when low outdoor temperatures resulted in very

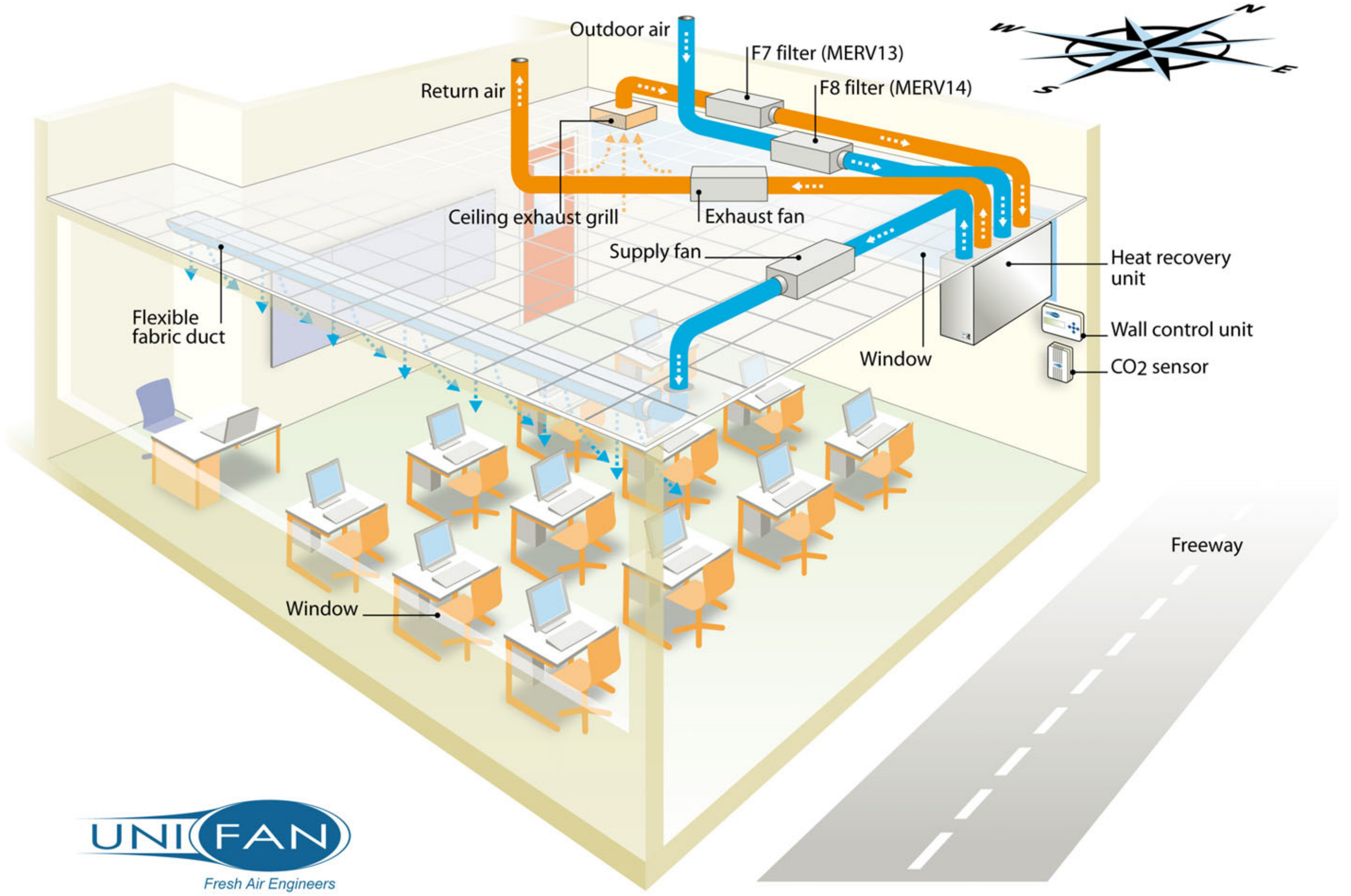

Fig. 2 Schematic picture of Unifan Octo 10 ventilation system in the intervention classroom

low classroom temperatures during early morning classes, the volume rate of the supply air was 1000 m^3 per hour between 8:45 and 19:00 and switched off at night.

Wind direction data

The percentage of time that the school was downwind from the highway was calculated. Downwind from the highway was defined as when the wind direction was between 10° and 170°, that is, within an angle of 80° from the perpendicular line to the road in the direction of the school (90°). Data on the wind direction per hour were obtained from the meteorology station at Schiphol airport, located about 8 kilometres from the school.

Air sampling

Indoor sampling equipment was placed in the back of the classroom, and measurements were performed at a height of approx.1.5 meters. Outdoor sampling equipment was placed on the rooftop, just above the study classroom. The inlets of the outdoor sampling equipment were situated approximately 11 meters above street level, 6 meters above highway level, and 2 meters above the top of the sound wall. Pictures of the indoor and outdoor sampling equipment are presented in the Supplementary Material.

PM10 and PM2.5 concentrations were measured with tapered element oscillating microbalances (TEOM 1400AB) at 50°C (Rupprecht and Patashnick, Albany, NY, USA). To prevent noise nuisance from the TEOM pumps, the indoor pumps were placed in a small storage room adjacent to the classroom. A factor of 1.3 was applied to adjust for underestimation due to evaporation of the volatile fraction in PM10 and PM2.5 (Ayers et al., 1999; Green et al., 2001). PM10 and PM2.5 concentrations were measured continuously and reported as 30-min averages.

BC was measured continuously with micro-aethalometers (AE51, AethLabs, San Francisco, CA, USA) with a time resolution of 5 min. The micro-aethalometer measured differential BC mass on a filter using 880 nm infrared light (Hansen et al., 1984). To prevent the filter ticket from overloading, the micro-aetholometers were replaced every school day during the lunch break. The exact stop and start time of each measurement was registered. Four devices were used, two for indoor measurements and two for outdoor measurements, in the same indoor-outdoor combination.

The indoor CO_2 concentration was measured with a Q-Trak (7565; TSI Inc., St Paul, MN, USA) at 5-min intervals.

Data quality and control

The size-selective inlets used for PM10 and PM2.5 (sharp cut cyclone) are in accordance with standard EPA design. Measurements and QA/QC procedures of the TEOM are in line with the Australian standard AS 3580.9.8 and received NEN EN ISO/IEC 17025:2005 accreditation in 2005. BC measurements were excluded when the attenuation was above 75 as this is an indication of overloading of the filter ticket (Dons et al., 2012; Virkkula et al., 2007). This resulted in exclusion of 25% of the data, mainly those collected during the weekends as the devices were changed only on schooldays. All data collected during the first 15 min after changing the devices were excluded. Parallel measurements were performed to compare the micro-aethalometers with each other on five Fridays during the sampling period, both indoors at our laboratory and outdoors at a nearby busy street. There were no systematic differences and a high correlation (R^2 = 0.99) was found between the readings obtained from the AE51 devices.

Data analysis

To allow comparison between PM and BC concentrations, 5-min average BC concentrations were transformed into 30-min average concentrations. The 30-min concentrations were calculated for half-hour periods with four or more valid 5-min average concentrations. If fewer than four measurements were available, the concentration was set to missing. This resulted in exclusion of <1% of the data.

PM10 and PM2.5 concentrations with more than 25% of data missing (measured in 10-second intervals) in the 30-min interval were noted as missing, resulting in the exclusion of 0.2% of the 30-min values. All measurements performed during the week of installation of the new ventilation system were excluded. There were no classes held during this week. Measurements performed during vacuum cleaning were also excluded.

The teacher's diary and the regular school schedule were used to classify all measurements into two categories: teaching hours and non-teaching hours. Non-teaching hours included lunch break, non-teaching hours on school days, and weekends and holidays.

As a result of the labor-intensive nature of the BC measurements and the potential overloading of the filter ticket, the number of 30-min average BC measurements measured during the study period was substantially smaller than that for PM10 and PM2.5, which were measured fully automatically. For instance, BC concentrations were not measured during the Christmas holiday, during 5 weekends, and during 2 days with extreme weather conditions (storm).

Outliers in the measurement data were checked by close inspection of the boxplots. In some cases, this resulted in the exclusion of the data. If there was no obvious flaw or other reason for the high concentrations, the outliers were kept in the dataset, as the analysis is based on comparison of the median I/O ratios, and the median is not sensitive to outliers.

All 30-min average PM10, PM2.5, and BC concentrations measured under different ventilation conditions were used to summarize and analyze the data, which was performed separately for teaching hours and non-teaching hours. To illustrate daily patterns in outdoor concentrations, 30-min average concentrations were averaged over all 24-hour periods within the given sampling periods.

The statistical differences between mean concentrations were assessed by t-test, and differences in indoor/outdoor ratios by Wilcoxon's signed rank test.

Statistical analyses were performed with SAS 9.1 (SAS Institute, Cary, NC, USA).

Results

CO_2 concentrations

During sampling period 1 (baseline), the existing ventilation system was switched off 69% of the time according to the teacher's diary, due to noise nuisance. This resulted in high CO_2 concentrations of 1811 ppm on average during teaching hours. However, the average CO_2 concentration was also high (on average 1376 ppm) during the 31% of the time when the existing ventilation system was switched on, probably as a result of restricted supply airflow through the overloaded filter. The mean CO_2 concentration during classes was 1760 ppm during sampling period 1 (baseline) and 798 after installation of the new ventilation system (sampling periods 2 and 3). As expected, the presence or absence of a filter in the system did not affect the CO_2 concentrations.

Indoor-outdoor relations

Figure 3 illustrates the average diurnal pattern in indoor and outdoor BC, PM10, and PM2.5 concentrations during the three sampling periods.

Outdoor BC concentrations were lowest in sampling period 3. This is a result of differing meteorology aspects, especially wind direction. The school was located downwind of the highway 32%, 43%, and 22% of time during sampling periods 1, 2, and 3, respectively.

Indoor particle concentrations are affected by a matrix of conditions that vary between sampling periods and over the day, including ventilation rate,

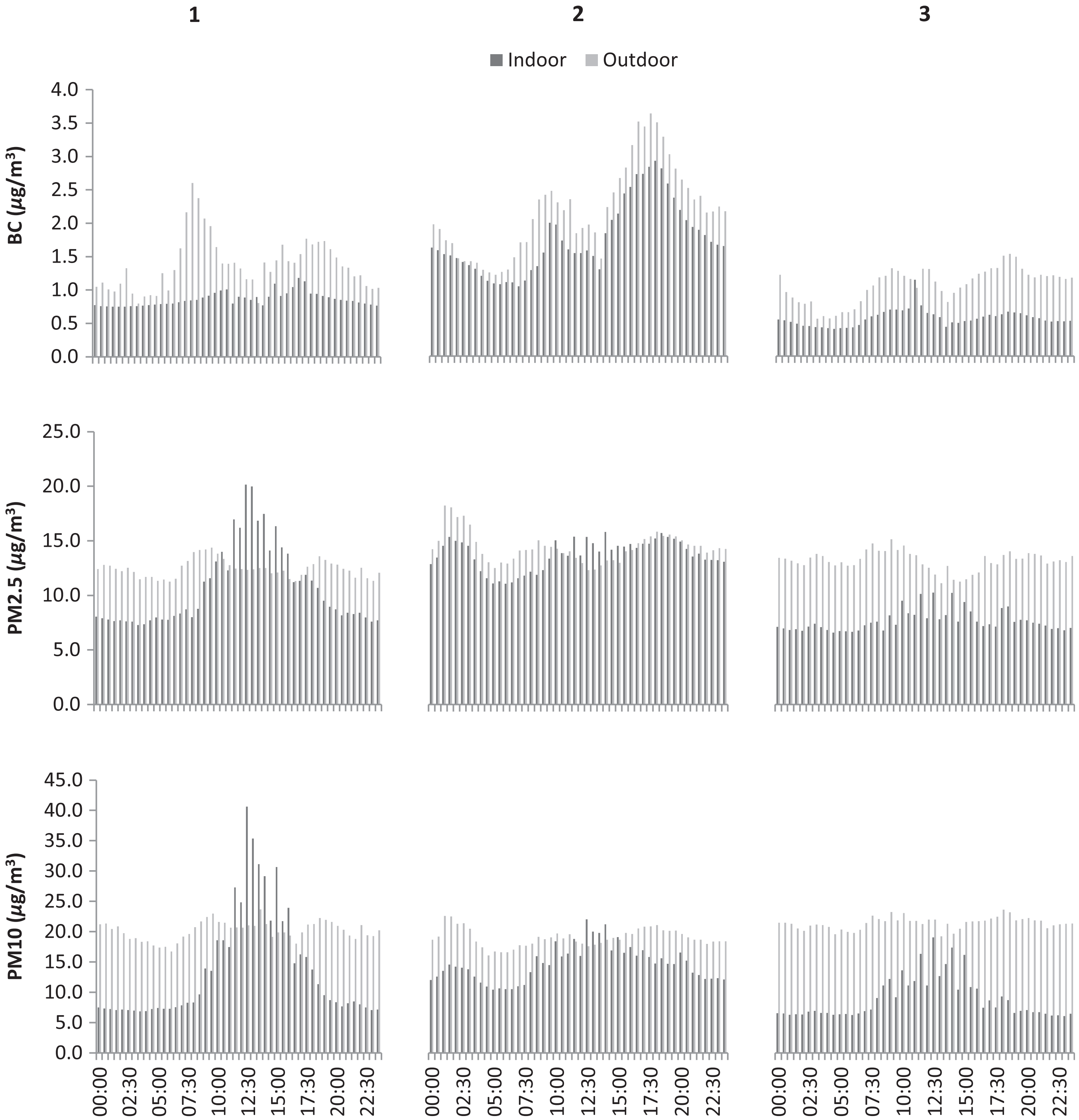

Fig. 3 Diurnal pattern in outdoor and indoor black carbon (BC), PM10 and PM2.5 concentration (μg/m^3) during sampling periods 1 (baseline), 2 (new ventilation system, without filter and 3 (new ventilation system with F8 filter). Bars represent 30-min average concentrations averaged over all 00-24 hour periods within the given sampling periods

indoor activities, and outdoor concentrations. During baseline (sampling period 1) with a low ventilation rate, high indoor PM2.5 and especially PM10 concentrations were measured during teaching hours that often exceeded the outdoor concentrations. Apparently, indoor-generated particles due to human activities are not effectively removed due to the low ventilation rate. During sampling period 2, with a high ventilation rate and no filtering of outdoor air, the indoor BC, PM10, and PM2.5 concentrations were much closer to the outdoor concentrations than during sampling periods 1 and 3. Indoor PM10, PM2.5, and BC concentrations were lowest in sampling period 3, both absolutely and relative to outdoor concentrations. In all three sampling periods, variations in outdoor BC concentrations (rush hour) were reflected in indoor BC concentrations, but most obviously during sampling period 2.

Table 2 Mean (sd) indoor PM10, PM2.5 and black carbon (BC) concentration (μg m $^{-3}$), during teaching and non-teaching hours for the three sampling periods (1 = baseline, 2 = without filter, 3 = with filter) and number of 30-min measurements for PM and BC

Sampling period	N (PM)	N (BC)	PM10	PM2.5	BC	PM10	PM2.5	BC	PM10	PM2.5	BC
	Teaching hours		Indoor			Outdoor			Median of indoor/outdoor ratios		
1	155	115	35.6 (20.8)***	19.6 (9.4)***	0.88 (0.67)*	19.1 (9.1)	11.2 (6.3)	1.31 (0.65)	1.62***	1.54***	0.64
2	152	97	28.9 (15.1)**	21.8 (0.9)***	2.03 (1.20)**	22.6 (11.8)	17.9 (11.5)***	2.54 (1.49)*	1.14***	1.13***	0.80
3	170	128	18.2 (0.8)**	10.9 (5,5)**	0.58 (0.46)*	20.9 (10.9)	12.2 (6.7)	1.16 (0.95)	0.75***	0.79***	0.51**
	Non-teaching hours		Indoor			Outdoor			Median of indoor/outdoor ratios		
1	991	513	9.9 (8.4)	9.1 (4.6)	0.80 (0.47)	20.0 (9.6)	12.5 (7.1)	1.39 (0.99)	0.42	0.73	0.64
2	1591	384	12.3 (10.2)	11.9 (8.9)	1.71 (1.04)	18.4 (11.3)	13.9 (10.9)	2.19 (1.25)	0.66	0.95	0.81
3	1103	737	5.8 (4.1)	5.5 (2.6)	0.49 (0.45)	21.2 (10.2)	13.1 (6.0)	1.06 (1.03)	0.34	0.55	0.48

*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$.

Table 2 summarizes the PM10, PM2.5, and BC concentrations measured indoors and outdoors during teaching hours and non-teaching hours. The median I/O ratios are presented as well. The number of valid 30-min BC measurements is much lower than the number of PM measurements for reasons described in the methods section.

The I/O ratios for PM10 and PM2.5 are significantly higher during teaching hours compared with non-teaching hours for all sampling periods, demonstrating the large contribution of indoor-generated particles to the total exposure. In contrast, I/O ratios for BC are similar during teaching hours and non-teaching hours. Scatter plots of indoor to outdoor concentration during teaching hours are presented in Figure 4. Scatter plots during non-teaching hours are presented in the Supplementary Material The intercepts are near zero, indicating that all indoor BC is of outdoor origin. The slope of the regression equations represents the fraction of outdoor particles penetrating indoors. The scatter plots in Figure 4 illustrate (indicated by the R^2) that during sampling period 3 (new ventilation system, with fine filter), outdoor concentrations explain a large part of the total variation in indoor BC concentration but only a small part of the variation in PM concentration, consistent with the large contribution of indoor sources to PM concentrations. During sampling period 2, the R^2 is relatively high for PM10 and especially for PM2.5, indicating a substantial contribution from outdoors, consistent with the ventilation conditions (no filter).

Performance of the new filtration system

To evaluate the ability of the F8 filter to reduce exposure to particles, the indoor-outdoor ratios during sampling period 3 were compared with those in sampling period 2. The ventilation rates are identical, the only difference being the presence (or absence) of the F8 filter. Table 2 shows that for PM10, PM2.5, and BC, the median I/O ratio decreased from 1.14, 1.13, and 0.80 in sampling period 2 to 0.75, 0.79, and 0.51 in sampling period 3, respectively. The decrease in the median I/O ratio was statistically significant for all three particles' metrics ($P < 0.001$, not shown). This implies that during teaching hours, a reduction in the I/O ratio of 34%, 30%, and 36% is achieved by the F8 filter for PM10, PM2.5, and BC, respectively. During non-teaching hours, the achieved reductions are 48%, 42%, and 41%, respectively.

To evaluate to what extent the new ventilation system with the F8 filter improves the indoor air quality in the classroom compared with the existing (baseline) situation, indoor/outdoor relations during sampling period 3 were compared with those in sampling period 1. During teaching hours, the median I/O ratios for PM10 and PM2.5 were reduced by 54% and 49%, respectively, and the median I/O ratio for BC was reduced by 20%. The results indicate that the higher ventilation rate of the new system more effectively removes indoor-generated particles. However, sampling periods 1 and 3 differ with respect to both filtration and ventilation rates, and those factors cannot be disentangled.

Discussion

This pilot study has shown that application of a fine F8 (MERV14) filter reduced the BC concentration inside an occupied classroom near the highway by 36% on average. PM10 and PM2.5 concentrations were reduced by 34% and 30%, respectively. The reduction percentages were calculated from the I/O ratios measured during 4 weeks of sampling with an F8 filter (sampling period 3) and without one (sampling period 2) in a newly installed ventilation system, under otherwise identical ventilation conditions. During non-teaching hours, the reduction percentages for BC, PM10, and PM2.5 were 41%, 48%, and 42%, respectively.

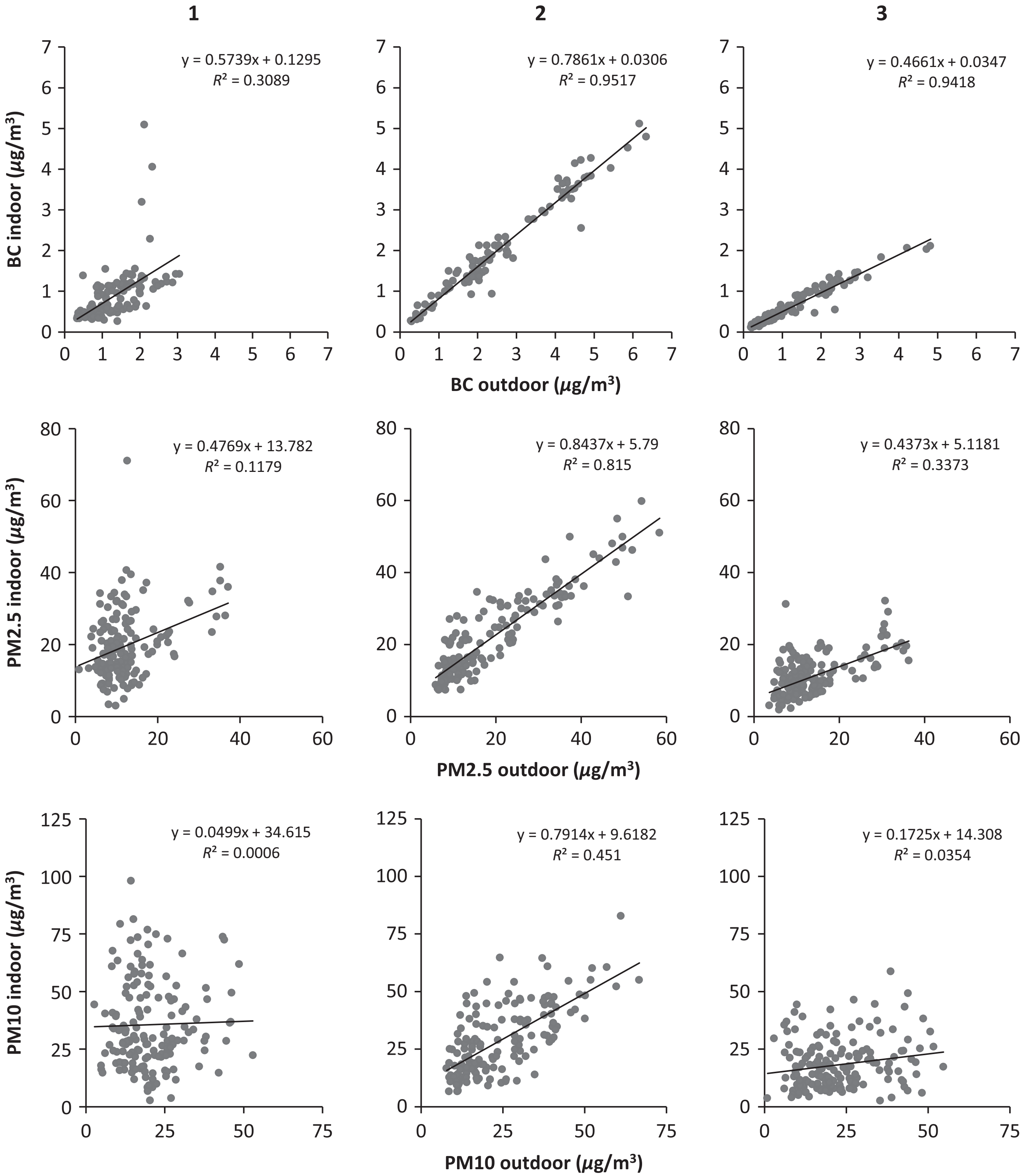

Fig. 4 Scatter plots of 30-min average black carbon (BC), PM10 and PM2.5 concentrations outdoor and indoor during sampling periods 1 (baseline), 2 (new ventilation system, without filter) and 3 (new ventilation system with F8 filter), during teaching hours

Compared with the few other studies that evaluated filtration effectiveness on particle concentrations in occupied classrooms, we found a somewhat lower efficiency of the filter system. In a study in Las Vegas, medium (MERV11) and high (MERV15) efficiency filters were installed in existing HVAC systems in three schools near roadways. The ability of the filter system to reduce BC particles ranged from 74% for the

MERV11 filter to 77% and 97% for the MERV15 filter (McCarthy et al., 2013). Polidori et al. (2013) tested the ability of an HVAC system equipped with MERV15 filters in schools in California and found 88% lower indoor than outdoor concentrations for both BC and PM2.5. The lower efficiency observed in our study compared with other studies cannot be explained by the contribution of indoor-generated particles, as BC concentrations in the classroom were not affected by indoor sources. Thus, the results of our study suggest that a substantial amount of unfiltered outdoor air enters the classroom, despite the fact that the supply airflow of the new ventilation system was substantially higher than the exhaust airflow. In the presence of a leaky envelope at this school, which was not designed with noise insulation and energy efficiency in mind, this may not have been sufficient to provide for a large enough net positive pressure to protect against infiltration. A limitation of our study is that we studied only one mechanical air filtration system with one type of filter in one classroom in one school. The impact of an air filtration system on classroom air quality varies with the building characteristics, occupancy, outdoor concentration, season, and ventilation conditions (Yu et al., 2014). We might have found different reduction percentages under other conditions. Nevertheless, our findings demonstrate that application of a new mechanical ventilation system with a fine filter significantly improved indoor air quality in a classroom near a highway.

Prior to the intervention period, baseline measurements were performed with the school's existing mechanical ventilation system under normal operating conditions, including filtration through an aged and overloaded F5 filter. The purpose of the baseline study (sampling period 1) was to evaluate indoor-outdoor relations in a classroom near the highway without any interventions. During the baseline study, high indoor PM10 and PM2.5 concentrations were measured during occupancy hours, probably due to the low ventilation rate. High ventilation rates contribute to the effective removal of indoor-generated particles (Abt et al., 2000; Chen and Zhao, 2011; Goyal and Khare, 2009); consequently, low ventilation rates result in a higher concentration of indoor-generated particles. During all three sampling periods, we found that BC exposure in the classroom came almost exclusively from outdoor sources. This is in agreement with other studies that measured BC concentrations in classrooms (Reche et al., 2014; Viana et al., 2014).

In contrast, the results of our study demonstrate that during all sampling periods, indoor sources largely contributed to PM10 exposure in the classroom. This was also observed in other studies and is a result of resuspension of settled dust due to human activities, which mainly influence the coarse fraction (Braniš et al., 2005; Janssen et al., 1999; Kingham et al., 2008; Morawska et al., 2013). Other studies generally find a reduced influence of indoor activities on the fine PM2.5 fraction (Morawska et al., 2013), but in our study PM2.5 concentrations were substantially elevated during teaching hours as well. It has been reported that emissions from textiles and organic matter (e.g., skin flakes, textile fibers) from human activities can contribute to high PM2.5 concentrations in classrooms (Amato et al., 2014; Rivas et al., 2014), which might explain the observed findings. Fromme et al. (2008) found that nearly 57% of the PM2.5 and 76% of the PM10 in German classrooms were generated indoors.

The contribution of indoor sources to indoor particle concentrations was substantial and varied over the day and between days. The class schedule and group size were the same during the whole study period. Although small differences (i.e., due to absent students) occurred, it is reasonable to assume that the *variation* in classroom activities (due to students entering and leaving the class, etc.) is similar during all three study periods. Therefore, it is unlikely that the contribution of indoor sources differed systematically between the sampling periods. Sampling periods 2 and 3 only differed with respect to the presence (or absence) of the filter, which is a strength of our study.

Maintenance

Mechanical ventilation with air filtration has been associated with air pollution and sensory pollution due to dusty or unhygienic ducts, filters, and vents (Beko et al., 2008). Aged filters have been associated with increased sick building syndrome symptoms and decreased work performance in studies of filtration maintenance in workplaces (Clausen, 2004; Seppänen and Fisk, 2002; Wargocki et al., 2004). In our study, we encountered a number of maintenance-related problems. Aged and overloaded medium-efficiency filters were present in the school's existing ventilation system, and F8 filters were delivered instead of the F9 filters ordered. Although this might be regarded as a 'flaw' in our study, it raises questions about the installation of the proper type of filters and proper maintenance in other, less thoroughly checked situations. There is no legal framework that guarantees good maintenance of ventilation systems and frequent replacements of filters in schools. However, filtration is only effective if the filters are frequently replaced and the ventilation system is properly maintained according to the manufacturer's recommendations (California Environmental Protection Air Resources Board, 2012).

Conclusions

Measured outdoor BC concentrations in Amsterdam are typically 1.5- to 2.5-fold higher at traffic sites compared with urban background locations (Helmink et al., 2014). This pilot study demonstrates that the F8 filter is able to lower the indoor BC and PM concentrations by about one-third. This implies that the application of a fine filter can reduce the exposure of schoolchildren to traffic-related air pollution at hot spot locations, but siting schools away from traffic is always preferred.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1. Installation of new F8 filterbag and F8 fiilterbag at the end of the study period.

Figure S2. Indoor and outdoor measurement equipment.

Figure S3. Scatter plots of 30-min average black carbon (BC), PM10 and PM25 concentrations during non-teaching hours

Table S1. Summary of study design and measurement periods

Table S2. Results of the regression analyses for black carbon (BC), PM2.5 and PM10 during teaching hours and non-teaching hours.

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