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Effect Of Ventilation On Chronic Health Risks In Schools And Offices

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January 4, 2013

This work was supported by the California Energy Commission, Public Interest Energy Research Program, Energy Related Environmental Research Program, under contract 500-09-049.

LBNL-6121E

ABSTRACT

This study provides a risk assessment for chronic health risks from inhalation exposure to indoor air pollutants in offices and schools with a focus how ventilation impacts exposures to, and risks from, volatile organic compounds (VOCs) and particulate matter (PM2.5). We estimate how much health risks could change with varying ventilation rates under two scenarios: (i) halving the measured ventilation rates and (ii) doubling the measured ventilation rates. For the hazard characterization we draw upon prior papers that identified pollutants potentially affecting health with indoor air concentrations responsive to changes in ventilation rates. For exposure assessment we determine representative concentrations of pollutants using data available in current literature and model changes in exposures with changes in ventilation rates. As a metric of disease burden, we use disability adjusted life years (DALYs) to address both cancer and non-cancer effects. We also compare exposures to guidelines published by regulatory agencies to assess chronic health risks. Chronic health risks are driven primarily by particulate matter exposure, with an estimated baseline disease burden of 150 DALYs per 100,000 people in offices and 140 DALYs per 100,000 people in schools. Study results show that PM2.5-related DALYs are not very sensitive to changes in ventilation rates. Filtration is more effective at controlling PM2.5 concentrations and health effects. Non-cancer health effects contribute only a small fraction of the overall chronic health burden of populations in offices and schools (<1 DALY per 100,000 people). Cancer health effects dominate the disease burden in schools (3 DALYs per 100,000) and offices (5 DALYs per 100,000), with formaldehyde being the primary risk driver. In spite of large uncertainties in toxicological data and dose-response modeling, our results support the finding that ventilation rate changes do not have significant impacts on estimated chronic disease burdens. Median estimates of DALYs are approximately doubled when the ventilation rates are halved and there is little reduction in health risks associated with doubling ventilation rates, but the very low baseline disease burden from the indoor exposures we considered makes this unremarkable. In exploring the full range of exposure concentrations, to find the fraction exceeding the Office of Environmental Health and Hazard Assessment's (OEHHAs) chronic reference exposure levels (cRELs) and United States Environmental Protection Agency's (USEPA) chronic reference dose (RfD) we found only minor shifts in exposure safety margins when ventilation was doubled or halved. We combined our exposure estimates with cancer potency factors published by OEHHA and USEPA to determine that the annual excess cancer risk per capita are below 1 in a million under all ventilation rate scenarios for individual pollutants. The results indicate that chronic health risks (cancer and non-cancer) associated with VOC and PM2.5 exposure in offices and schools are low and thus the chronic disease burden or health benefits of ventilation changes are likely to be well below both the level of detection by health surveillance studies and the level of regulatory thresholds.

INTRODUCTION

According to Klepeis et al. (2001), the United States (US) population spends about 18% of its time in non-residential buildings. It is also documented that indoor exposures to pollutants contribute significantly to total daily exposures (Edwards et al. (2001), Son et al. (2003), Logue et al. (2011)). Several studies in commercial buildings in the U.S. (e.g., Daisey et al. (1994), Ekberg, (1994), California Air Resources Board (2004), Eklund et al. (2008), Godwin and Batterman (2008), Shendell et al. (2004), Bennett et al. (2011)) have identified a variety of pollutants present at higher concentrations indoors than outdoors. Given the range of commercial building types and contaminant sources, indoor pollutant concentrations in these buildings will vary significantly depending on many factors including human activities, building function, and structural features.

Numerous studies, for example Bluyssen et al. (1996), Wargocki et al. (1999), and Wargocki et al. (2000), have highlighted the importance of reducing indoor pollutant loads to improve occupant perceptions of indoor air quality and office worker productivity. Increased ventilation (increased outdoor air supply) is a means of reducing concentrations of pollutants emitted indoors and studies have reported significant improvement in measures of work and school performance when ventilation rates are increased (e.g., Wargocki et al. (2000), Seppanen et al. (2006a, 2006b), Wargocki and Wyon (2007)). Satisfaction with air quality has improved and sick building syndrome (SBS) symptoms have decreased with increased ventilation rates (e.g., Seppanen et al. (1999), Chao et al. (2003), Fisk et al. (2009), Sundell et al. (2011)), although not in every study (e.g., Jaakola et al. (1991)). Milton et al. (2000) reported that doubling ventilation rates reduced absence among office workers. The modeled economic benefits of improvements in acute health effects and work performance, resulting from increased ventilation rates, are large (Fisk et al. (2011)). However, these studies have not directly related work performance, satisfaction with indoor air quality, or SBS symptoms with indoor pollutant concentrations and have not considered impacts on chronic health effects.

Historically, ventilation has been provided to buildings to control odors, to avoid acute health symptoms, and to protect buildings from moisture damage. A review of the current literature on air quality, health effects and ventilation in commercial buildings reveals an important gap. There are studies that focus on measuring pollutant concentrations and/or ventilation rates in commercial buildings (often independently). There are studies that focus on linking ventilation rates in commercial buildings with acute health effects. But there are very few studies that focus on ventilation, its effect on concentrations of pollutants indoors, and the associated chronic health effects.

ASHRAE's minimum ventilation standard (ASHRAE (2010)) and the California Energy Commission's Title 24 Standards (California Energy Commission (2008)), specify minimum ventilation rates for maintaining indoor air quality in commercial buildings. In this paper, we provide input for such standards by estimating the links among ventilation rates, indoor pollutant concentrations, and chronic health effects that could arise from the occupant's exposures to pollutants of concern.

METHODS

The risk assessment methodology comprises four steps, (i) hazard characterization, (ii) exposure assessment, (iii) dose-response assessment and (iv) risk characterization (NRC, 2009). In the next three sections of this report, we describe our methods for hazard, exposure and dose-response evaluations. The characterization of risk is covered in the Results and Discussion sections.

Hazard characterization

To select pollutants of potential concern, we reviewed literature on indoor air pollutant concentrations in offices and schools. We evaluated the effect of ventilation on indoor pollutant concentrations in commercial buildings through modeling and systematic evaluations of available studies. We assessed ventilation impacts on indoor air concentrations as a function of basic chemical properties. We used a mass-balance model to characterize the dependence of pollutant removal and occupant exposures on pollutant vapor pressure and partitioning behavior--the associated extent to which the pollutant resides in air, on airborne particles, and on indoor surfaces.

For volatile organic compounds (VOCs) with dominant indoor sources we found that ventilation rate can have a large impact on exposures. This suggests that a need to control exposures to VOCs may determine minimum ventilation requirements in commercial buildings. The modeling effort allowed us to identify VOCs whose concentrations are responsive to ventilation rate changes and whose sources are predominantly located indoors. These methods are described in detail in prior documents (Parthasarathy et al. 2011, Parthasarathy et al. 2012). The results of these papers were used to identify compounds whose

health effects should be analyzed as a function of ventilation rates. These compounds were considered in the present paper.

Exposure assessment

A literature search identified indoor air monitoring studies that were conducted in offices and schools in the United States and provided a complete range of the data types needed--ventilation rates, indoor and outdoor concentrations of particulate matter (PM) and VOCs, and building characteristics. Data available in this literature set were used to conduct the exposure assessment.

The datasets utilized for office buildings are the following:

> The United States Environmental Protection Agency Building Assessment Survey and Evaluation (BASE, 2006) study: The BASE study was carried out in 1994-1998 in 100 U.S. office buildings that were randomly selected. The heating ventilation and air-conditioning systems were studied and environmental sampling was carried out. The ventilation rate was estimated using various methods -- we rely on ventilation rates estimated from peak indoor carbon dioxide (CO_2) concentrations converted to air change rates using supplied building data. Integrated 9-hour VOC measurements (55 VOCs) representing a work day were completed in each building, simultaneous outdoor concentrations were also measured. Samples for particles less than 2.5 micrometers (PM2.5) and less than 10 micrometers (PM10) were collected using filters, which were weighed before and after sampling to estimate the PM concentrations. Sampling was carried out at three indoor locations, and one outdoor location. In addition, other environmental parameters such as temperature and relative humidity were also measured.
>
> Small and medium commercial buildings (SMCB) study (Bennett et al. (2011)): Concentrations of 30 VOCs were measured in 37 California commercial buildings. The buildings were selected for sampling on a semi-random basis, and were geographically representative of small and medium commercial buildings in California. Sampling was carried out in ten office buildings where simultaneous indoor–outdoor VOC concentrations, along with PM2.5 and PM10 were measured. Ventilation rates were measured by the sulfur hexafluoride (SF_6) tracer-decay method. Temperature, relative humidity, indoor and outdoor CO_2 were also measured.

Figure 1 shows the distribution of air change rates, in air changes per hour (ACH), in office buildings from the BASE and SMCB datasets.

For schools, we used data from the following study:

> The California Portable Classrooms study (California Air Resources Board, (2004)): This study was carried out by the California Air Resources Board and the Department of Health Services between April 2001 and February 2002. The first phase included a mail survey sent to 1000 schools as well as the mailing of passive formaldehyde samplers to two-thirds of the schools. The second phase included site-specific samples (for aldehydes, VOCs, mold spores, pollen, biological pollutants, particle count, pesticides, metals, PAH's and allergens in floor dust) collected in 201 portable classrooms at 67 randomly selected schools in California. The passive

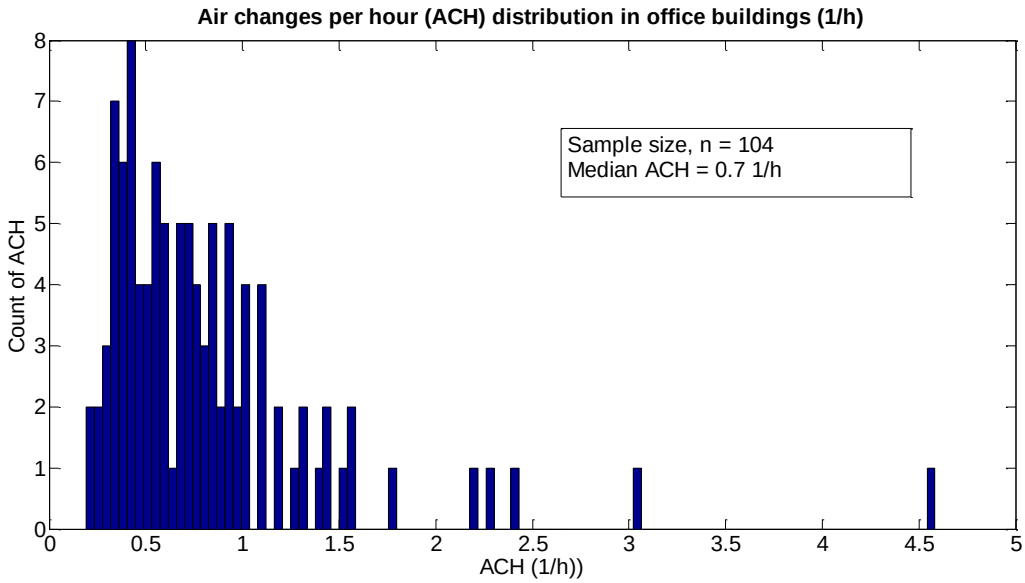

Figure 1 : ACH distribution in offices

formaldehyde sampling was carried out for 7-10 days in Phase I, and in Phase II 6-h sampling was carried out. Most of the schools were suburban. Elementary schools were sampled more than middle or high schools. Ventilation rates were not directly measured in this study, we calculated the ventilation rates from indoor and outdoor CO_2 measurements. For particle modeling, we assumed a default value for air recirculation rates. Figure 2 shows the ACH distribution in schools obtained from this dataset.

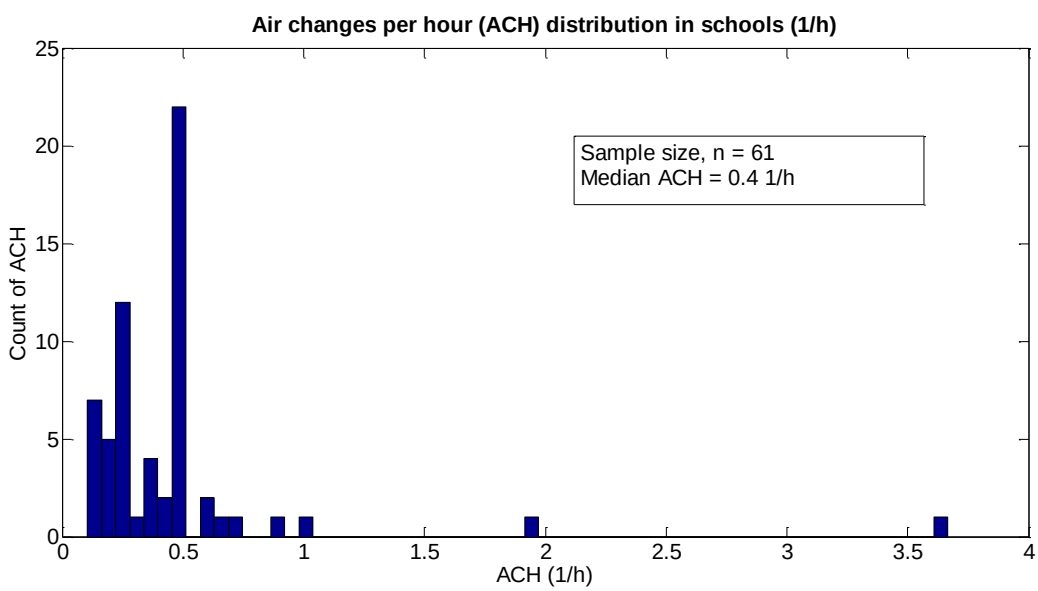

Figure 2 : ACH distribution in schools

Pollutant concentration, ventilation rate, and building characteristics information such as floor area and ceiling height were obtained from the databases associated with these studies. With these data sets we were able to calculate indoor pollutant emission factors (EFs). The equations used to calculate values of EF are presented subsequently.

Mass balance models were applied to calculate values of EF from existing data and to evaluate the effect of changing ventilation rates on indoor air concentrations of VOCs and particles. Figure 3 shows the model schematic and model parameters.

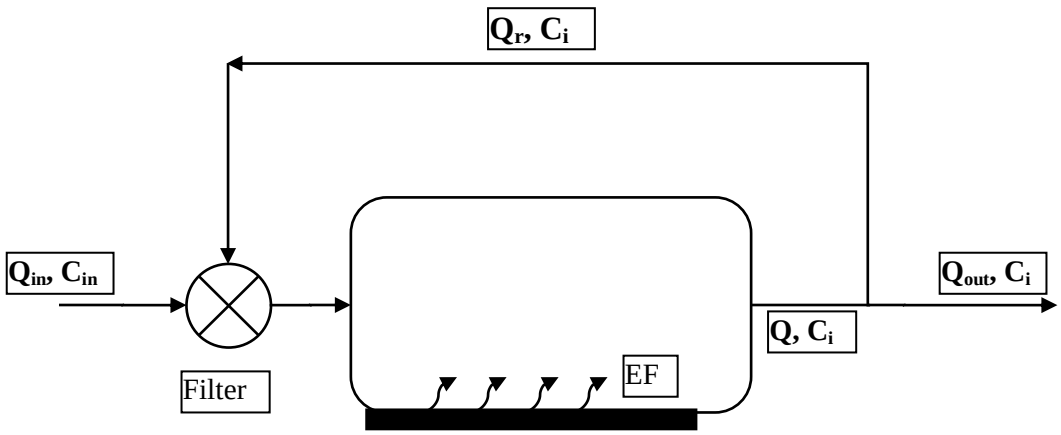

Figure 3 : Schematic of a well mixed room

For VOCs, the following is the mass balance expression (assuming the filter does not remove VOCs)

$$V_i \times \frac{dC_i}{dt} = C_{in} \times Q_{in} + C_i \times Q_r - C_i \times Q_{out} + EF \times A_i \qquad (1)$$

Under steady state conditions, and assuming $Q_{in} = Q_{out}$ the expression simplifies to

$$C_i = C_{in} + \frac{EF \times A_i}{Q_{out}} \qquad (2)$$

The following equation was used to calculate the emission factors

$$EF = C_{in} - C_{out} \times ACH \times h \qquad (3)$$

Where,

V_i = volume of room (m^3)

C_i= concentration of pollutant in the room (µg/m^3)

C_{in}= concentration of pollutant in inlet (outdoor) air (µg/m^3)

Q_{in}, = flow rates of outdoor air into the room (m^3/h)

Q_{out} = flow rate of indoor air leaving the room and being exhausted to the outdoors (m^3/h)

Q_r = flow rate of recirculated air (m^3/h)

EF = floor area normalized pollutant emission factor (µg/m^2-h)

A_i is the floor area of the room in m^2

Equation 4 was first used to calculate values of *EF* using published data and then, subsequently was used to calculate values of indoor VOC concentration as the air change rate (ACH) was changed, where air change rate

$$ACH = \frac{Q_{in}}{V_i} \qquad (4)$$

With V_i being the indoor volume.

The mass balance expression for particulates is as follows

$$V_i \times \frac{dC_i}{dt} = 1 - \varepsilon_{filter} \times C_{in} \times Q_{in} + 1 - \varepsilon_{filter} \times C_i \times Q_r - C_i \times Q + EF \times A_i - v_d \times C_i \times V_i \qquad (5)$$

At steady state the expression simplifies to

$$C_i = \frac{EF \times A_i + C_{in} \times Q_{in} \times (1 - \varepsilon_{filter})}{Q_r \times (\varepsilon_{filter}) + Q_{out} + v_d \times V_i} \qquad (6)$$

The following formula was used to calculate the emission factors for particulate matter

$$EF = \frac{C_i \times Q_r \times \varepsilon_{filter} + Q_{out} + v_d \times V_i - C_{in} \times Q_{in} \times (1 - \varepsilon_{filter})}{A_i} \qquad (7)$$

Where,

ε_{filter}= efficiency of the filter for particles, assumed to be same for indoor air and outdoor air particles

v_d=the first order deposition loss coefficient for particulate matter on indoor surfaces (1/h)

Equation 7 was used to calculate emission factors for particles from published data and Equation 6 was used for the calculations of indoor concentrations as air change rates were changed.

The filter efficiency estimates used in our calculations are for MERV8 and MERV 13 filters. Minimum efficiency reporting value (MERV) is a filter rating system (ASHRAE (1999)). Filters with higher MERV rating are more efficient at removal of particles. The efficiency values in Table 1 were utilized. They are based on calculations by Riley et al. (2002) for new filters with an upward adjustment to account for increases in filter efficiency over their service life (Hanley et al. 1994).

Filter	Efficiency for PM2.5	Efficiency for PM10
MERV8	18%	24%
MERV13	70%	74%

Table 1 – MERV ratings and filter efficiencies used in the model

PM2.5 mass concentrations are available from the BASE dataset and the SMCB study. PM2.5 counts (0.5 µm – 2.5 µm) were available for schools from the California Portable Classrooms study. Based on Chan and Noris (2011), we assumed an effective particle diameter of 0.86 µm, to compute mass concentrations.

$$M = \frac{\pi}{6}\rho \times \frac{\#count}{F} \times d^3 \qquad (8)$$

Where,

M = Mass concentration (μg/m^3)

count = Number of particles counted by the particle counter per minute

F = Volumetric flow rate of air through the particle counter (m^3/minute)

d = diameter (μm)

ρ = particle density = 1.65 mg/ m^3

Because particle mass concentrations for schools were estimated based only on counts from a limited range of PM2.5 particles, we applied an adjustment factor to estimate the total PM2.5 mass. Based on indoor sampling in stores which have similar filtration systems (Chan et al. 2012), we determined that approximately 35% of PM2.5 mass is made up of particles with diameters are less than 0.5 μm. Thus, the particle mass concentration from equation 6 was multiplied by 1.35.

The concentrations of the pollutants were evaluated under three different scenarios (i) existing distribution of ventilation rates, (ii) ventilation rates are halved relative to current conditions, and (iii) ventilation rates are doubled relative to current conditions. A dose-response relationship was applied to these concentrations to evaluate the subsequent reduction or increase in health risks associated with the changes in ventilation rates. The pollutant concentrations were calculated under different scenarios, and a bootstrap procedure was applied to obtain robust estimates of the median and the 95% confidence interval. See Figures in Appendix for details on individual pollutants.

Dose-response analysis

The following metrics were used to characterize disease burdens in the dose-response analysis

(i) Disability adjusted life years associated with non-cancer and cancer effects, for VOCs and PM2.5
(ii) Excess cancer risks
(iii) Percent of pollutant concentrations that exceed reference levels published by the California EPA's Office of Environmental Health Hazard Assessment (OEHHA) and the U.S. Environmental Protection Agency (U.S. EPA).

Disability adjusted life years (DALYs) are defined by the World Health Organization (World Health Organization, 2008) as "years of healthy life lost", and calculated as the sum of Years of life lost (YLL) and Years of life disabled (YLD). Within the target populations, YLL depends on both the number of early mortalities and lost life expectancy attributable to the early mortalities and YLD depends on number of incident cases of disability, length of the case and its disability weight. Using this approach allows us to quantify different health outcomes in terms of a common metric, which is used for comparisons across pollutants.

We employ the methods of Huijbregts et al. (2005) to determine the DALYs attributable to the unit intake of a pollutant. This approach uses the three equations below. The symbol ∂ refers to change or difference, and the derivative term functions as a single parameter.

$$DALY_{non-cancer} = \frac{\partial DALY_{non-cancer}}{\partial Dose} \times \partial Dose \qquad (9)$$

$$DALY_{cancer} = \frac{\partial DALY_{cancer}}{\partial Dose} \times \partial Dose \quad (10)$$

$$Total\ DALY = DALY_{non-cancer} + DALY_{cancer} \quad (11)$$

Our methodology draws upon prior work by Logue et al. (2012) which estimated the DALYs associated with residential exposures.

For particulate matter (PM2.5), we used dose response relationships developed by the U.S. EPA (U.S. Environmental Protection Agency 1999) for criteria outdoor pollutants. The chronic health outcomes considered in this report, largely based on availability of dose response relationships were chronic bronchitis, stroke and mortality. The following equations were used

$$\Delta Incidence = -y_o \times \ e^{-\beta \Delta PM_{2.5}} - 1 \ \times Population \quad (12)$$

Where,

y_o = baseline incidence of outcome of interest ($y_{o,mortality} = 7.9 \times 10^{-3}$, $y_{o,chronic\ bronchitis} = 0.4 \times 10^{-3}$, $y_{o,stroke} = 0.2 \times 10^{-3}$, Logue et al. 2012)

β = PM2.5 coefficient ($\beta_{mortality} = 6.5 \times 10^{-3}$, $\beta_{chronic\ bronchitis} = 9.1 \times 10^{-2}$, $\beta_{chronic\ bronchitis} = 2.5 \times 10^{-2}$

$\Delta Incidence$ = Change in incidence of the outcome relative to baseline incidence rates

The incidence vales were converted to DALYs using DALYs per effect data available in literature (Logue et al. 2012). The YLD DALYs associated with stroke (11.7 DALYs per incidence) and chronic bronchitis (1.2 DALYs per incidence) and the YLL DALYs associated with mortality (1.4 DALYs per incidence) were per incidence of the outcome were used.

All the DALY estimates were calculated as population-wide DALYs per year. The target populations were occupants of offices and schools, with estimated numbers as indicated in Table 2.

Building type	Type of population	Population	Source
Offices	Adults	40 million	Fisk et al. (2011)
Schools	Children	55.5 million	US Census Bureau (2012)

Table 2 – Target population for risk assessment in offices and schools

The cancer potency factors published by OEHHA (OEHHA 2009) and EPA (U.S. Environmental Protection Agency 2012) were also used to estimate how the cancer risk changes for individuals exposed to VOCs under current and altered ventilation rates. The following formula was used to calculate the cancer risks.

$$Cancer\ risk = \frac{C_i \times BR \times ED \times CPF \times ADAF}{BW \times AD} \quad (13)$$

Where,

C_i = indoor air concentration (μg/m^3)

BR = breathing rate of target populations (m^3/h)

ED = period over a lifetime when exposure occurs (days)

CPF = cancer potency factor (mg/kg-day)

$ADAF$ = Age-dependent adjustment factor, which accounts for change in susceptibilities across various age groups

BW = Body weight of the exposed individual (kg)

AD = Averaging duration over which the risk is evaluated, typically it is 70 years for an individual (years)

The inputs for the cancer risk assessment are provided in Table 3.

Parameter	Adult	Children (6-16 years)	Sources
Breathing rate	15 (m^3/day)	15 (m^3/day)	U.S.EPA Exposure Factors Handbook (2011)
ADAF	1	3	
BW	70 kg	6-11 years – 31.8 kg 11-16 years – 56.8 kg	
AD	70 years	70 years	

Table 3 - Inputs for estimating excess cancer risk

Adjustments were made for time spent in offices and schools using the factors in Table 4.

Location	Time spent	Time adjustment factor
Offices	10 hours/day, 5 days/week, 50 weeks/year	0.29
Schools	7 hours/day, 5 days/week, 35 weeks/year	0.14

Table 4 - Time adjustment factors

We also compared the median estimates of concentrations in offices and schools to concentration guidelines or limits published by the U.S. EPA and OEHHA. The guidelines and limits were selected to be health protective. We compared the exposure distributions to U.S. EPA's chronic reference dose (RfD) and to OEHHA's chronic reference exposure levels (CRELS). The percentile rank of the concentration distribution under current ventilation rate that exceeds the reference levels was compared to the percentile ranks when the ventilation rates were halved or doubled.

In addition, the median concentrations were compared to health guidelines set by OEHHA and the U.S. EPA. We estimated the percentile scores of the compound distributions that exceeded the health guidelines.

Uncertainty analysis

There are very large uncertainties associated with the toxicological data and methods that are used for dose-response analysis. Huijbregts et al. (2005) have quantified the uncertainties associated with the DALY estimates. The error bars on the DALY estimates indicate the 2.5^{th} and the 97.5^{th} percentile confidence intervals for DALY estimates based on uncertainty. We did not estimate the additional uncertainties associated with the exposure estimates, since they are quite small compared to the toxicological data and dose-response methods uncertainty estimates. Because DALY calculations do not apply an age-weighting factor, variations in susceptibilities in the population are not quantified.

RESULTS

Health risks of VOCs and their dependence on ventilation rates

Results from our risk assessment include estimates of DALYs and DALY changes and excess cancer risk changes. Three scenarios are presented—current ventilation rates, ventilation halved, and ventilation doubled. Table 5 and Figures 4 through 6 provided detailed results on the health burden associated with office worker exposures to VOCs and PM2.5. Figure 4 shows the DALYs due to non-cancer effects, Figure 5 shows the DALYs due to cancer effects, and Figure 6 shows the excess cancer risk associated with exposure. The bars represent the 2.5th and 97.5th confidence intervals with respect to uncertainty for these DALY estimates. In comparing median estimates, we note that non-cancer DALYs are highest for acetaldehyde and toluene. Total annual non-cancer DALYs under current ventilation rate conditions are 60 (0.5-10,500). When ventilation rates are doubled the median DALYs are 55 (0.4-9900) and when ventilation rates are reduced by half the median DALYs are 90 (0.7-15,900). Within the uncertainty bounds, there are no statistically significant changes in the disease burden associated with ventilation rate changes. But it should be noted that, based on the uncertainties in the toxicological and dose-response parameters used for DALY estimates many outdoor air pollution control measures enacted via regulation can also result in health benefits that lack the statistical significance needed to observe the results in health surveillance studies. The results here reveal that halving the ventilation rates increases health risk estimates notably, but doubling the ventilation rates has a smaller impact due to the non-linear relationships between ventilation rates and indoor pollutant concentrations.

Annual DALYs	Current ACH	ACH/2	ACH*2
Non cancer effects, population wide DALYs	60 (0.5,10500)	90 (0.7,15900)	55 (0.4,9900)
Cancer effects, population wide DALYs	1790 (70,46500)	2490 (100,64700)	1360 (52,35300)
Annual cancer risk			
Per caput risk in a million	0.8 (0.6,2.7)	1.3 (1,4.7)	0.7 (0.6,1.9)

Table 5 – VOC disease burden in offices

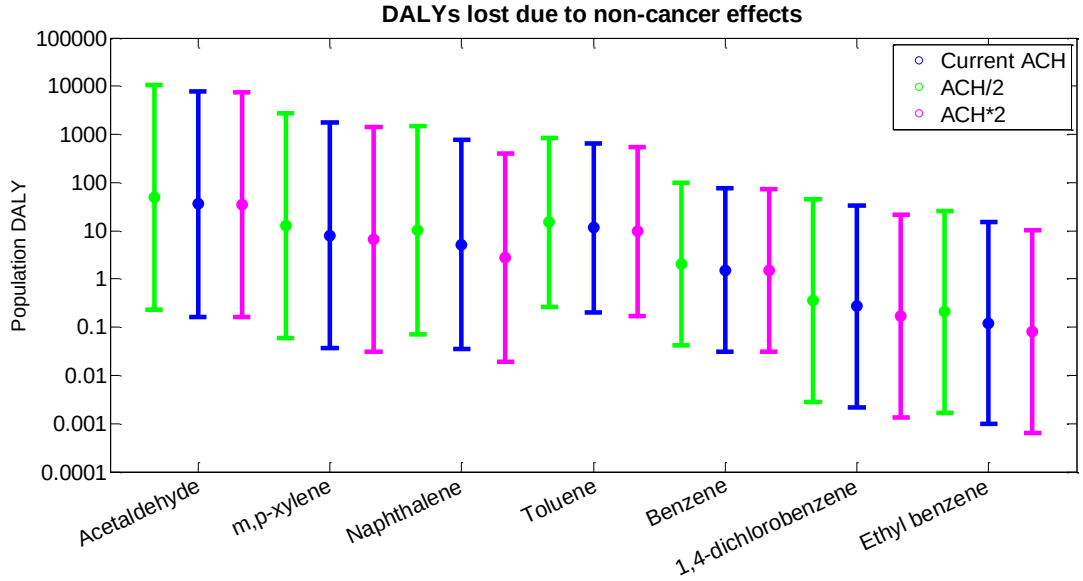

Figure 4 : Population-wide DALYs lost due to non-cancer effects in offices

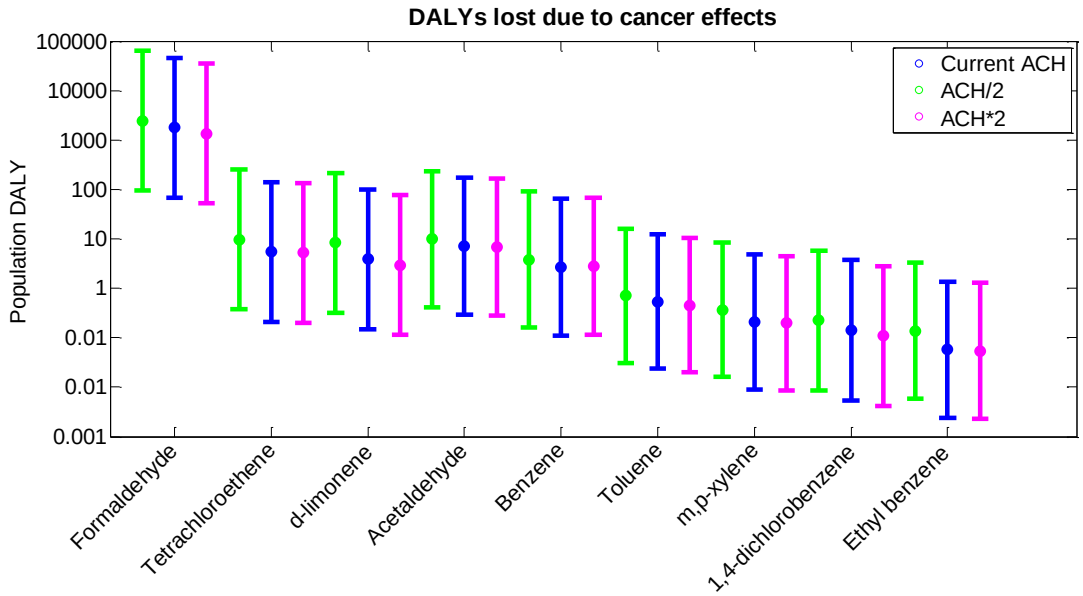

Figure 5: Population-wide DALYs lost due to cancer effects in offices

From Figure 5, we can see that formaldehyde is the primary driver of cancer disease burden in offices. The total median DALYs at current ventilation rates are 1790 (70-46,500) years. The median DALY estimates are roughly doubled when ventilation rates are halved, and no significant reductions in DALYs are seen when the ventilation rates are doubled. Similarly in Figure 6, total cancer risks are also lower than 1 in a million, with halving the ventilation rates the cancer risk is seen to be about 1.3 in a million and there is very little change even in median cancer risk estimates when the ventilation rates are doubled. The total increased individual cancer risk attributable to halving the ventilation rates is about 0.5 in a million. No individual pollutant's health risk is projected to exceed 1 in a million.

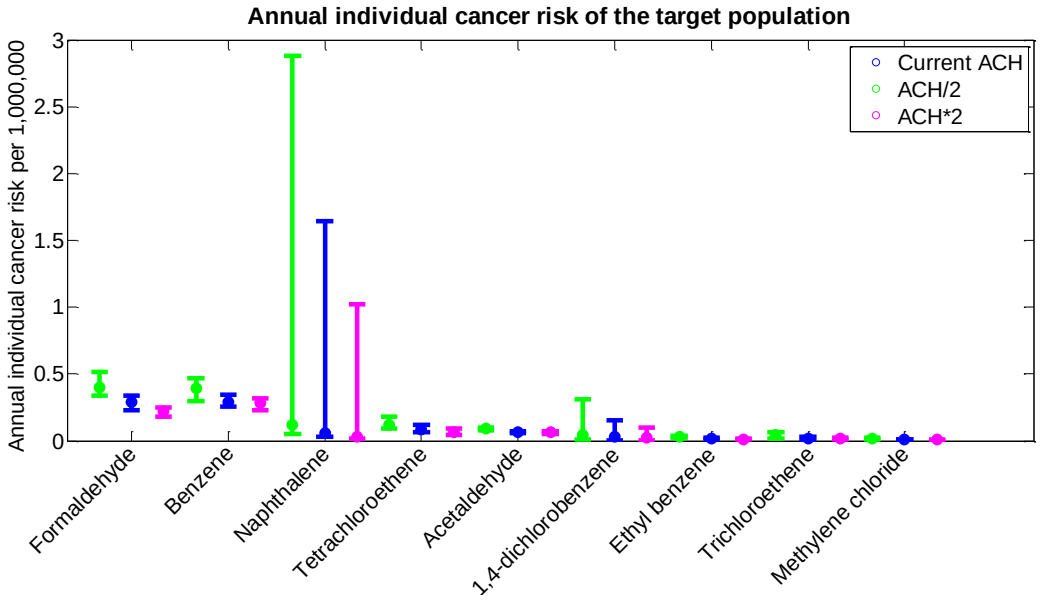

Figure 6 : Annual cancer risk of an individual working in office buildings

Table 6 and Figures 7-9 and Table 6 provide analogous results for schools. Cancer related DALYs are again much higher than non-cancer related DALYs. Total non-cancer DALYs, 40 (0.3,7600) years, do not change much with doubling the ventilation rates, 40 (0.2,6300) years, while DALYs increase to 60 (0.4,9900) years with a halving of the ventilation rates.

Annual DALYs	Current ACH	ACH/2	ACH*2
Non cancer effects, population wide DALYs	40 (0.3,7600)	60 (0.4,9900)	40 (0.2,6300)
Cancer effects, population wide DALYs	1400 (54,36700)	2310 (90,60000)	820 (30,21400)
Per capita cancer risk in a million	0.6 (0.5,0.7)	1.3 (1,1.7)	0.5 (0.4,0.6)

Table 6 – VOC disease burden in schools

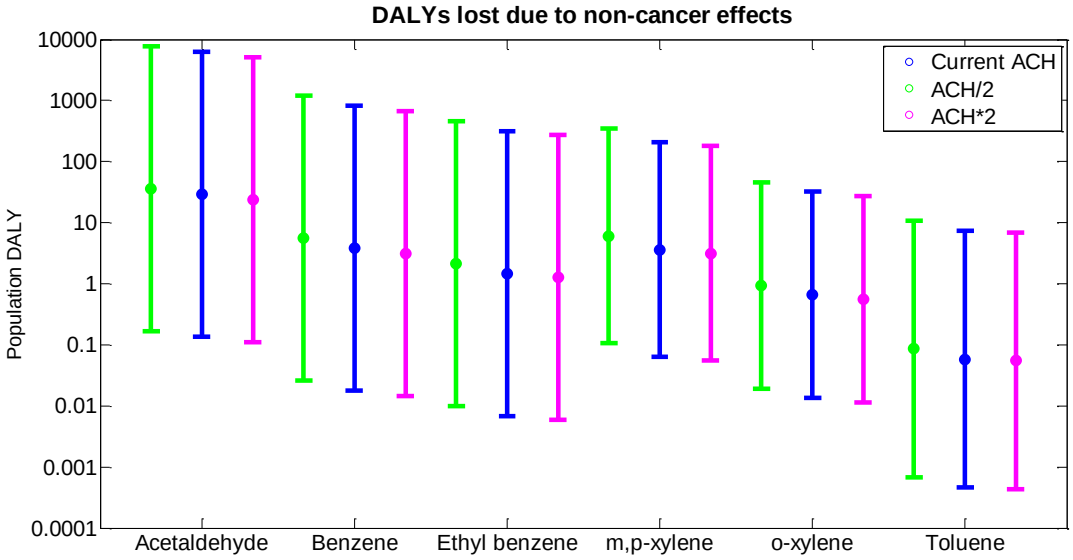

Figure 7: Population-wide DALYs lost due to non-cancer effects in schools

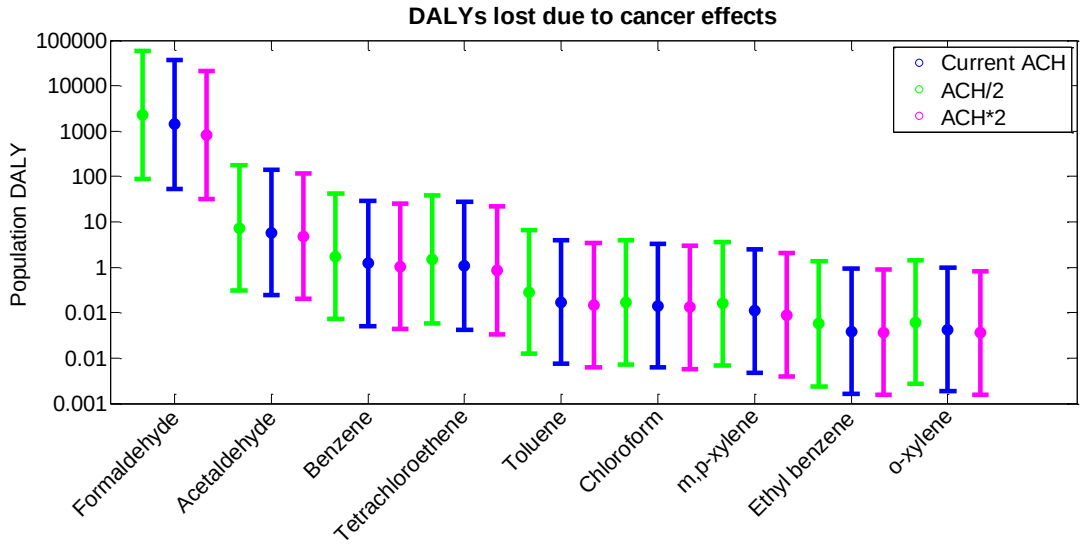

Figure 8 : Population-wide DALYs lost due to cancer effects in schools

Formaldehyde is also the dominant contributor to cancer disease burden in schools, and median risk estimates are seen to be sensitive to ventilation rate changes. The cancer DALYs are again projected to change from 1400 (54,36700) years at existing ventilation rates to 2310 (90,60000) years with ventilation rates halved. Doubling the ventilation rates produces only a very small reduction in disease burden. Total individual cancer risk in schools is seen to be about 0.6 in a million, with halving the ventilation rates the cancer risk is about 1.3 in a million and there is a very small change even in median cancer risk estimates when the ventilation rates are doubled. The total increased cancer risk attributable to halving ventilation rates is about 0.7 in a million. No individual pollutant's health risk is seen to exceed 1 in a million.

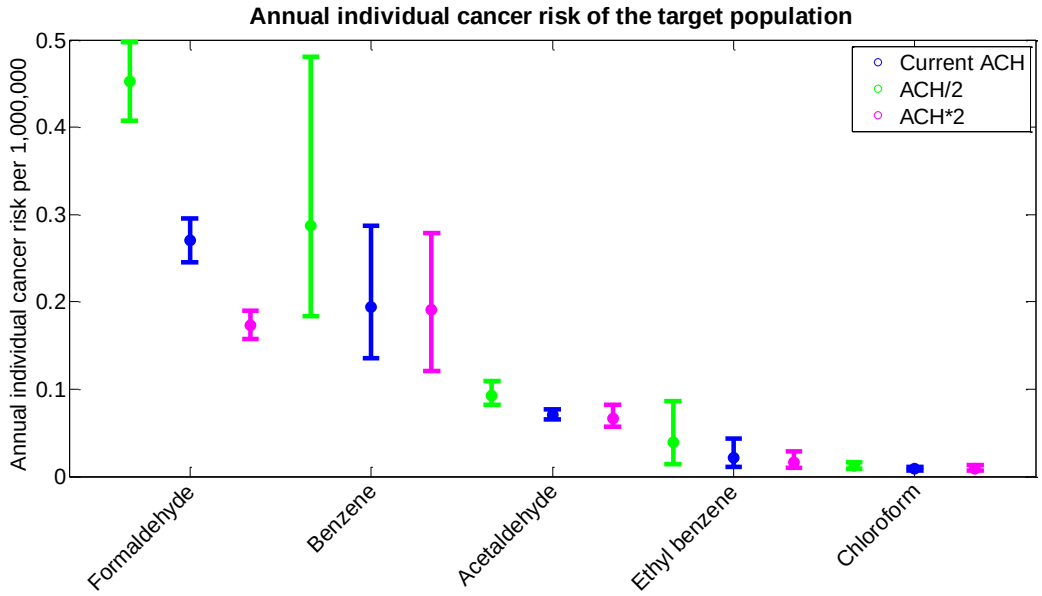

Figure 9: Annual cancer risk of a child in school

Health risks of particles and their dependence on ventilation rates

As seen in the following tables, PM2.5 is the major risk driver in both offices and schools, however modeling results show that PM risks are more sensitive to changes in efficiency of filters used than in changes in ventilation rates. Table 7 and 8 provide the estimated disease burdens in offices and schools, at existing ventilation rates, with ventilation rates halved, and with ventilation rates doubled. The DALY estimates do not differ significantly when the ventilation rates are changed. The total DALYs associated with particle exposure (60,700 DALYs in offices and 79,100 DALYs in schools) is significantly higher than all individual VOC pollutants. From the DALY estimates for schools and offices, risk from PM exposure in schools and offices are both significantly higher than risks associated with VOCs. Because the outdoor air is the primary source of particles, DALY's from particles decrease slightly with a halving of ventilation rates.

Table 7 PM disease burdens in offices

Offices	Current ACH		ACH/2		ACH*2	
	MERV8	MERV13	MERV8	MERV13	MERV8	MERV13
Chronic bronchitis population-wide incidence	37500	8900	32700	8500	40200	9600
Stroke population-wide incidence	700	200	600	200	700	200
Mortality population-wide incidence	6400	1400	5500	1300	6900	1500
Population-wide annual DALYs (chronic bronchitis)	45000	10700	39300	10200	48300	11600
Population-wide annual DALYs (stroke)	6700	1900	5700	1900	6700	1900
Population-wide annual DALYs (mortality)	9000	2000	7700	1900	9700	2100

Table 8 PM disease burdens in schools

Schools	Current ACH		ACH/2		ACH*2	
	MERV8	MERV13	MERV8	MERV13	MERV8	MERV13
Chronic bronchitis population-wide incidence	49700	15600	42500	12800	58600	17100
Stroke population-wide incidence	800	300	700	200	1000	300
Mortality population-wide incidence	8400	2400	7100	2000	10200	2700
Population-wide annual DALYs (chronic bronchitis)	59700	18800	51000	15400	70400	20600
Population-wide annual DALYs (stroke)	7600	2900	6700	1900	9500	2900
Population-wide annual DALYs (mortality)	11800	3400	10000	2800	14300	3800

Effects of changes in ventilation rates on indoor concentrations relative to exposure limits

We developed concentration distributions of the pollutants in offices and schools. The simple mass balance model at steady state was applied, and the concentration distributions were developed under the two scenarios: i) halving the ACH and ii) doubling the ACH. We provide the concentration distributions under all the scenarios in the Appendix for each individual pollutant. With compounds such as octanal that have strong indoor sources only, concentrations decrease with increased ventilation rates. With compounds that have strong outdoor sources such as benzene, halving the ACH slightly increases the concentration and doubling the ACH does not impact the concentration distribution strongly. With compounds that have comparable sources indoors and outdoors such as acetaldehyde, we see that decreasing ventilation rates increases the concentrations and doubling the ventilation rates does not significantly alter the concentrations.

We discuss here the results for formaldehyde and acetaldehyde concentration distributions (in offices) since these compounds are of most interest due to their low regulatory thresholds. For formaldehyde, we see an almost linear increase in concentrations with a decrease in ACH, and similarly a linear decrease in concentrations with increase in ACH. The entire distribution of formaldehyde concentrations in all scenarios is seen to exceed OEHHAs chronic REL. This is unsurprising given that OEHHAs chronic REL is lower than most typical indoor levels. Acetaldehyde is seen to exhibit an almost linear increase in concentrations with decrease in ACH. The effect of doubling ACH, however, does not cause an approximate linear decrease in concentrations. Most of the distribution is seen to exceed EPAs RfC when the ACH is halved, only some outliers exceed the RfC under current ACH, and concentration distribution does not exceed the RfC when the ACH is doubled. We see similar patterns with formaldehyde and acetaldehyde distributions in schools.

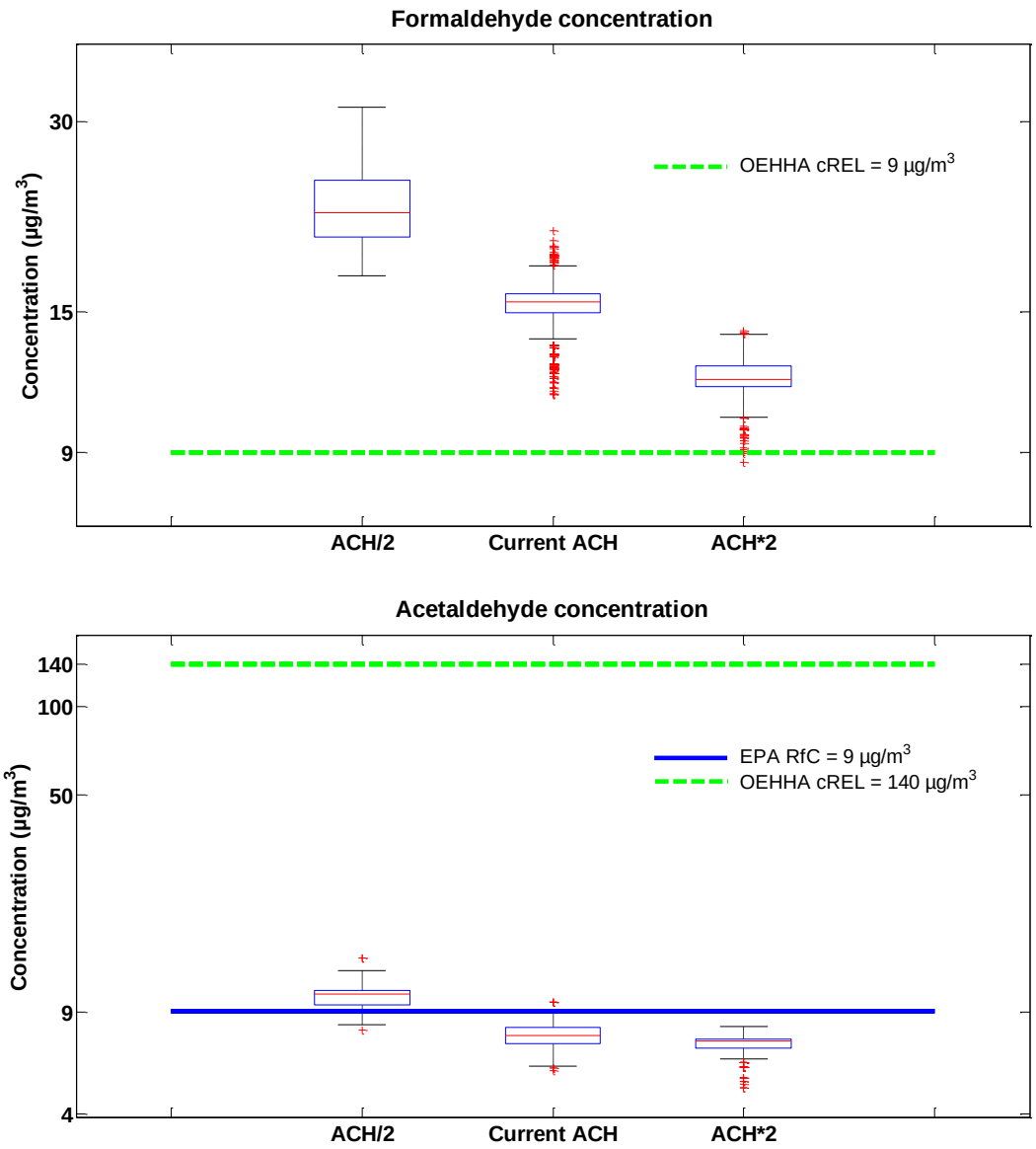

Figure 10: Concentration distributions for formaldehyde and acetaldehyde compared to reference exposure levels.

DISCUSSION

Logue et al. (2012) estimated the chronic disease burden from indoor pollutant exposure in residences. The study reported that about 1100 DALYs per 100,000 people were lost annually, excluding radon and second hand tobacco smoke. We estimated the DALYs associated with a smaller number of pollutants and the DALYs in offices and schools were seen to be approximately 150 DALYs per 100,000 people in offices and 140 DALYs per 100,000 people in schools. The risks are lower than in residences, however due to limited data availability we did not estimate risks from as wide of an array of pollutants. Also, the smaller amount of time spent in offices and schools than in homes partially explains the differences in total disease burden.

Since PM2.5 is the dominant risk driver, we calculated the DALYs associated with outdoor exposure to PM2.5, assuming that people are exposed at the California Ambient Air Quality Standard annual mean of 12 μg/m^3 outdoors, we assumed people spend 30% of their time outdoors (Klepeis et al. 2001). The DALYs associated with chronic bronchitis, stroke and mortality is approximately 180 DALYs per 100,000 people. These DALYs estimates are similar to our projected DALYs from exposures in schools and offices, indicating that risks outdoors and in offices and schools are of comparable magnitudes.

The cancer risks were below 1 in a million for all individual VOCs. The change in risk with changes in ventilation is below the level of one in 100,000 to one in 1,000,000 that has traditionally motivated regulation of outdoor air pollutant exposures. In summary, we see that particulate matter and formaldehyde are the major contributors to chronic health risk in schools and offices. These pollutants can have strong indoor and outdoor sources, which is especially important to consider when evaluating health effects variations with ventilation rates. Both in schools and offices we see an increase in risk with lowering ventilation rates, the risk reduction is not linearly proportional to reduction in ventilation rates. Overall, the risks of chronic health effects are small indicating that ventilation rate standards should not be based on chronic health risks. We conclude that ventilation rate standards should be based on a need to lower acute health effects such as sick building syndrome symptoms, and to provide appropriate air quality to improve worker efficiency.

ACKNOWLEDGMENTS

This work was supported by the California Energy Commission, Public Interest Energy Research Program, Energy Related Environmental Research Program, under contract 500-09-049. The authors thank Marla Mueller for project management and members of the project advisory committee for reviewing a draft of this document.

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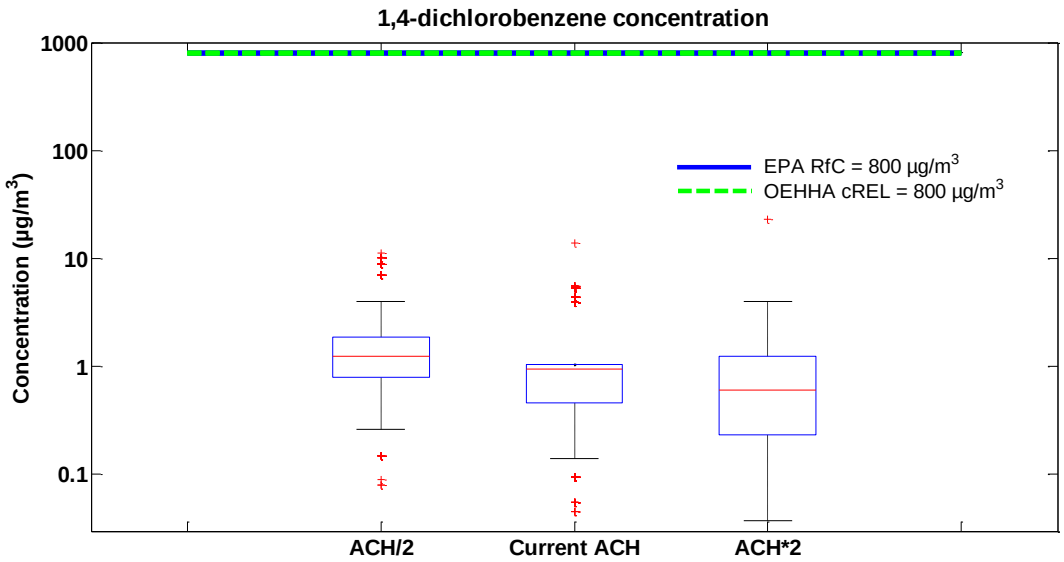
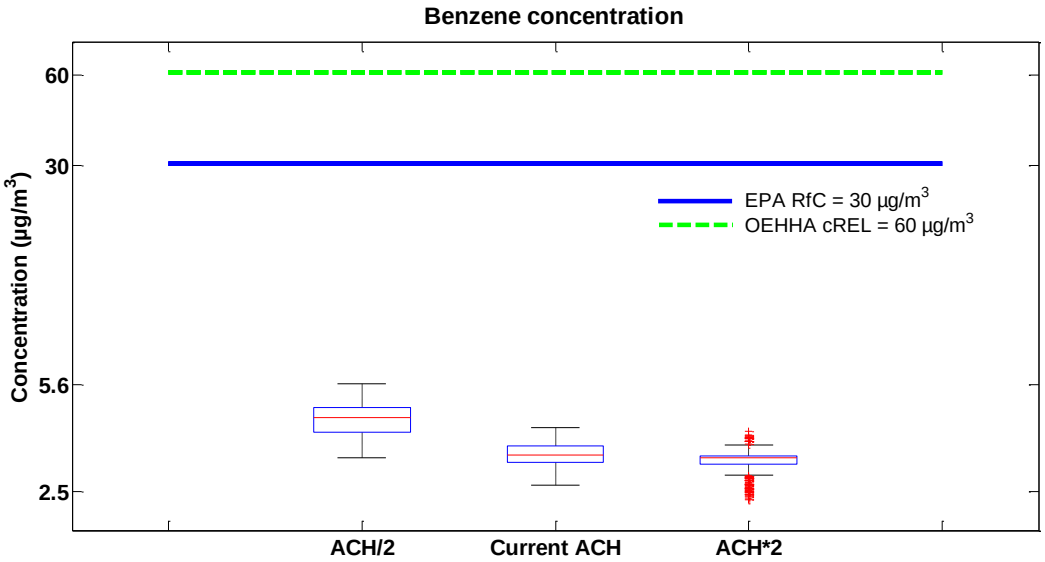
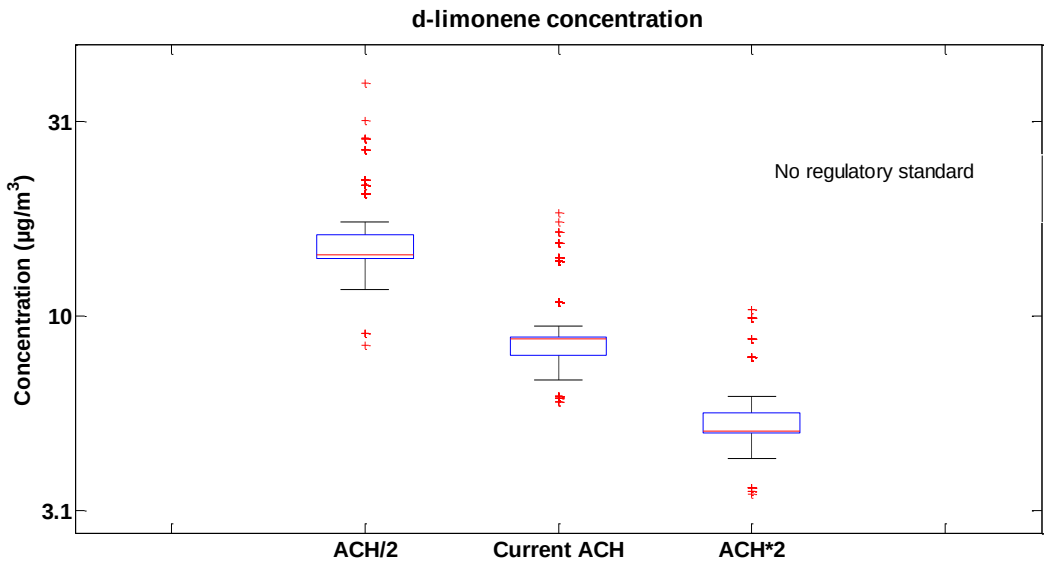
APPENDIX

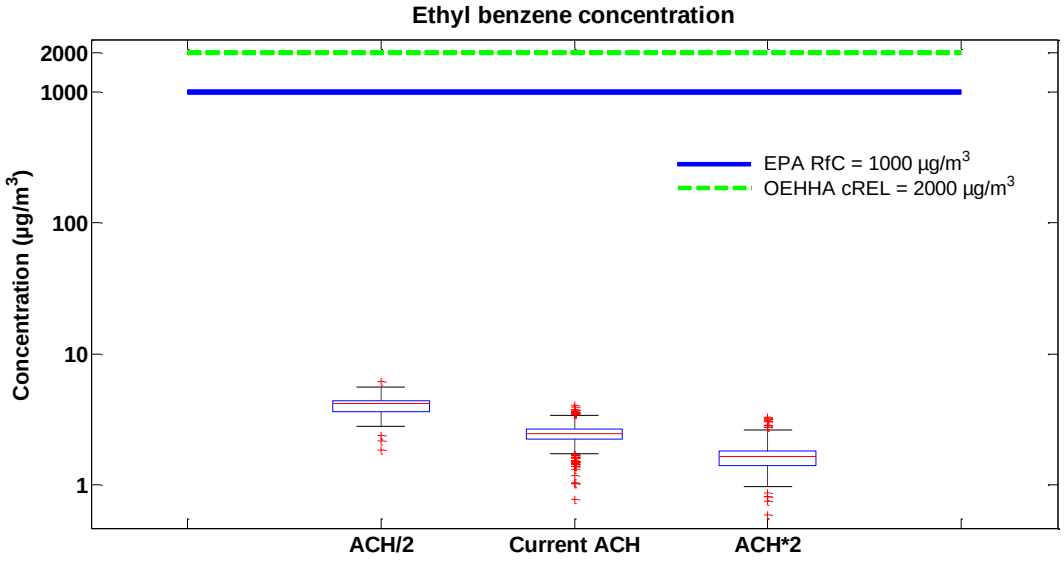
The following series of figures represent the distribution of pollutant concentrations measured in the original studies, and the variation in their distributions when the ACH is halved or doubled. The initial set of figures represent the concentration distributions in office buildings, which are followed by the figures with the concentration distributions in schools.

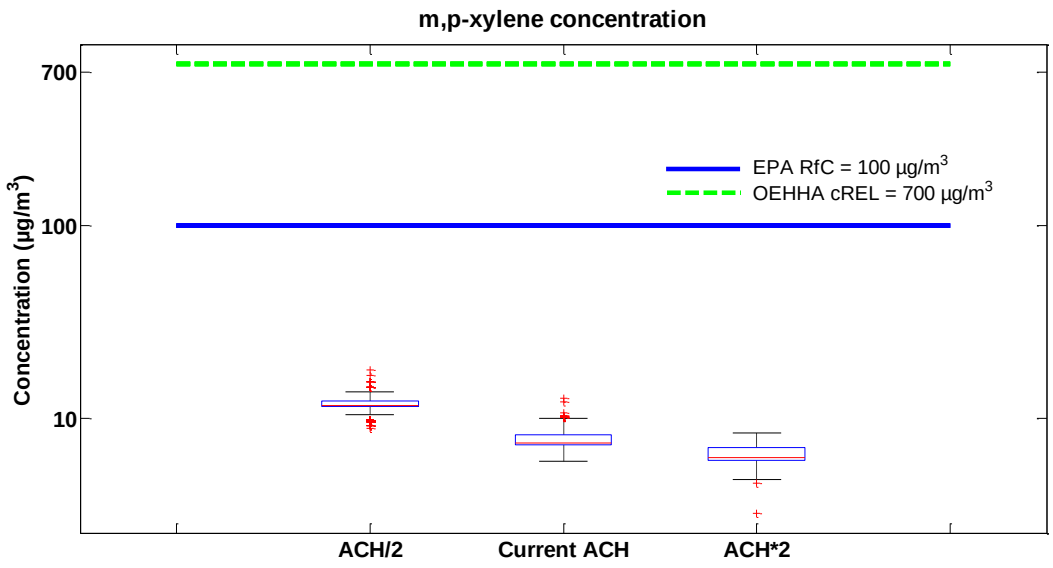
The following figures contain three boxplots. The boxplots indicate the concentration distributions at different ventilation rates. The boxplot at Current ACH is the actual data, the boxplots at the ACH/2 and ACH*2, show the calculated concentrations distributions. The values were generated for ACH/2 and ACH*2 conditions using bootstrapping, where Matlab software was used to uniformly sample from the data, and generate the median for the sampled data.

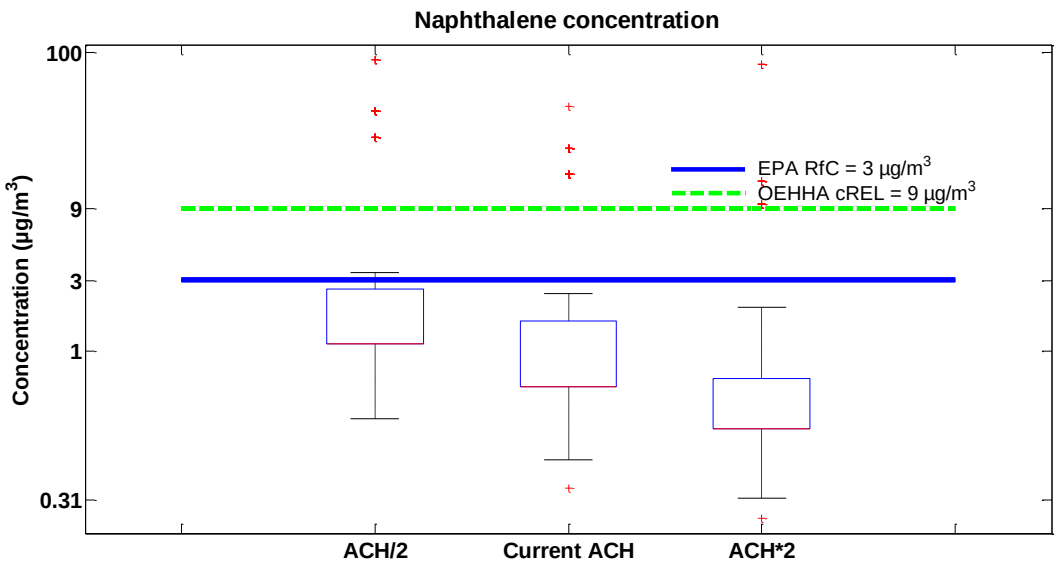


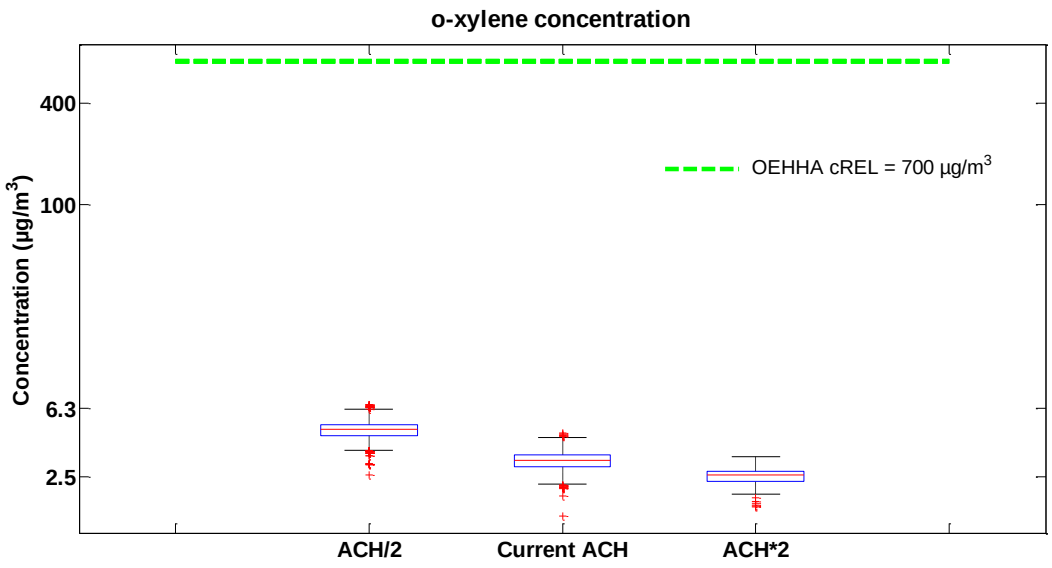


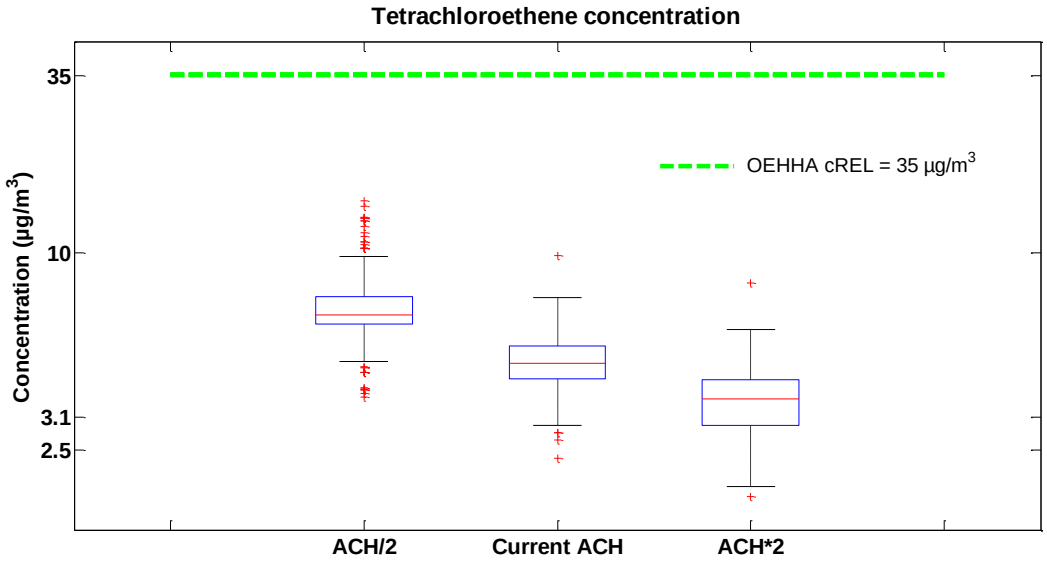

d-limonene concentration
Concentration (µg/m3)
31
10
3.1
No regulatory standard
ACH/2
Current ACH
ACH*2

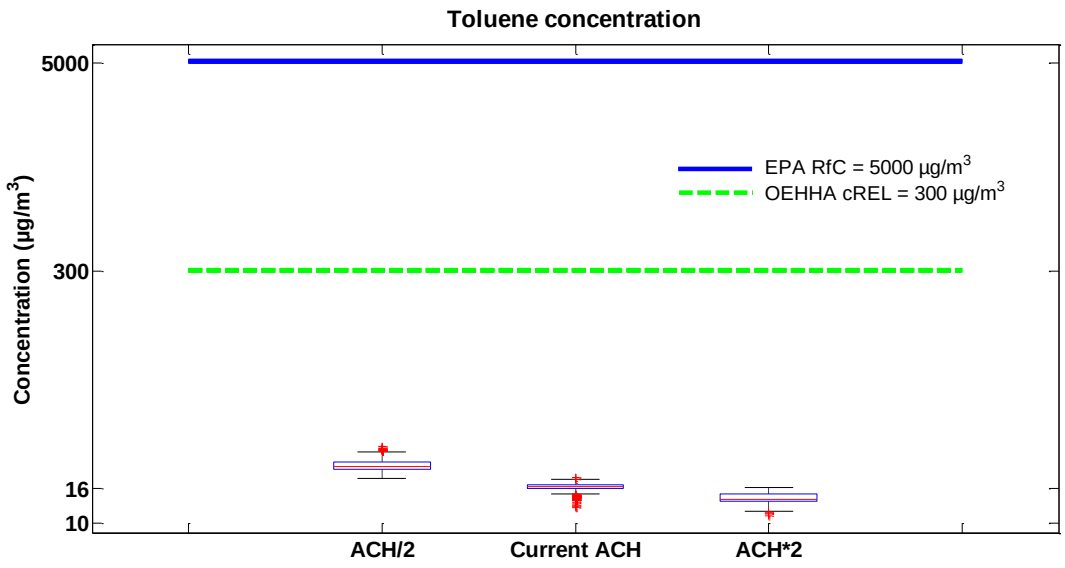

Ethyl benzene concentration
Concentration (µg/m3)
2000
1000
100
10
1
EPA RfC = 1000 µg/m3
OEHHA cREL = 2000 µg/m3
ACH/2
Current ACH
ACH*2

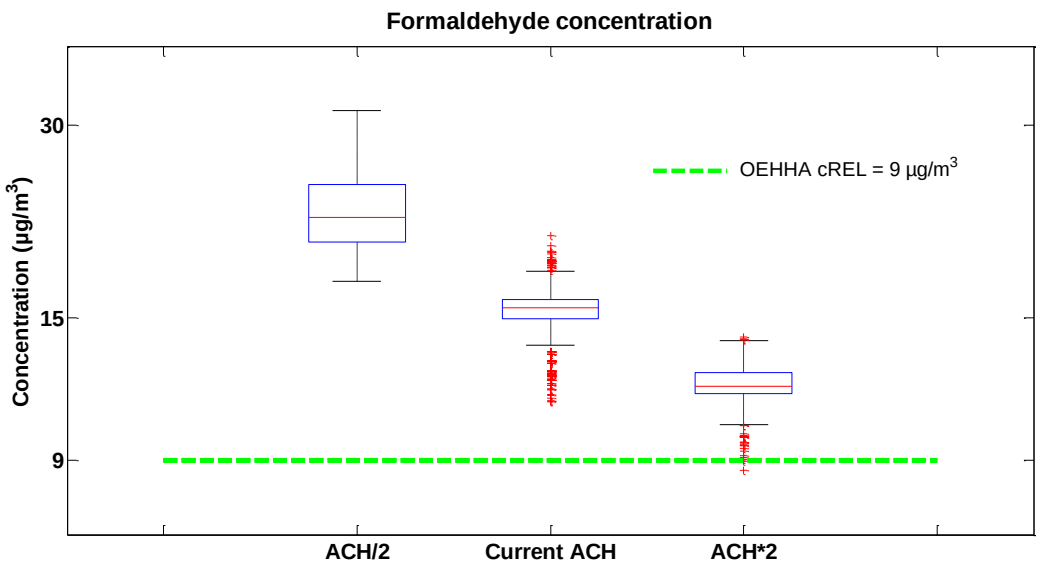

m,p-xylene concentration
Concentration (µg/m3)
700
100
10
EPA RfC = 100 µg/m3
OEHHA cREL = 700 µg/m3
ACH/2
Current ACH
ACH*2

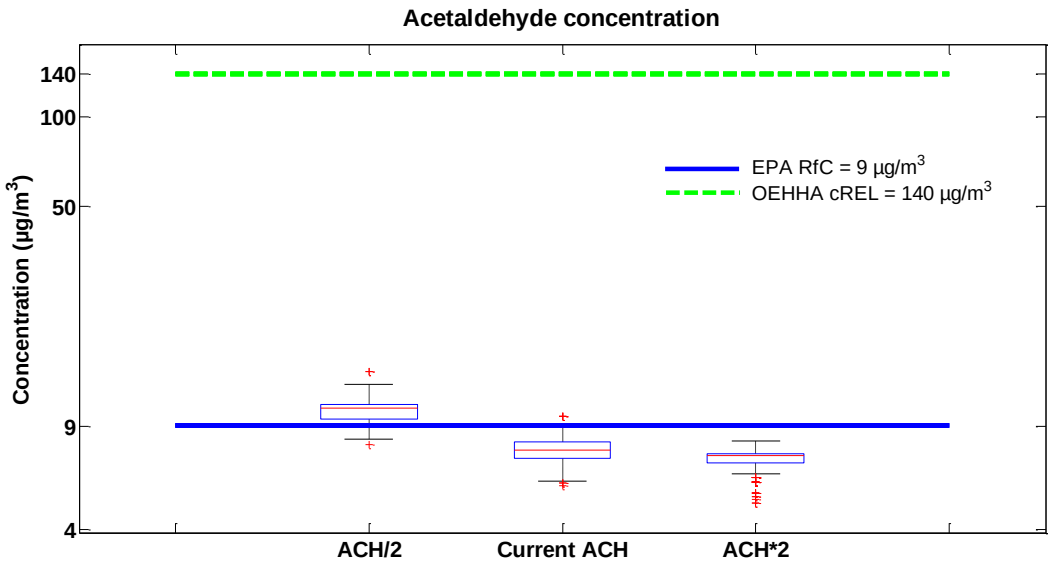

Naphthalene concentration
Concentration (µg/m3)
100
9
3
1
0.31
EPA RfC = 3 µg/m3
OEHHA cREL = 9 µg/m3
ACH/2
Current ACH
ACH*2


o-xylene concentration
Concentration (µg/m3)
400
100
6.3
2.5
OEHHA cREL = 700 µg/m3
ACH/2
Current ACH
ACH*2

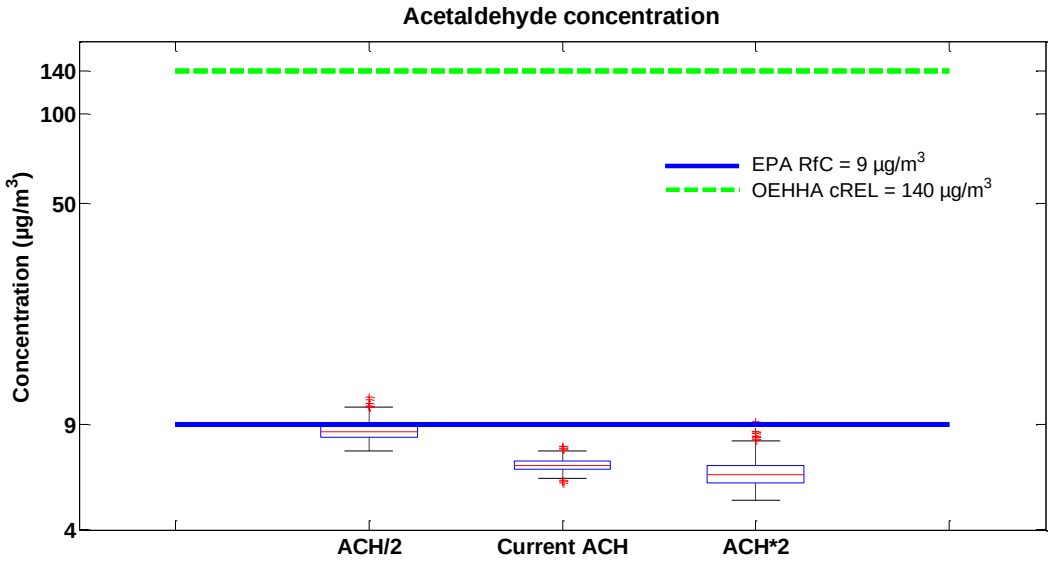

Tetrachloroethene concentration
Concentration (µg/m3)
35
10
3.1
2.5
OEHHA cREL = 35 µg/m3
ACH/2
Current ACH
ACH*2

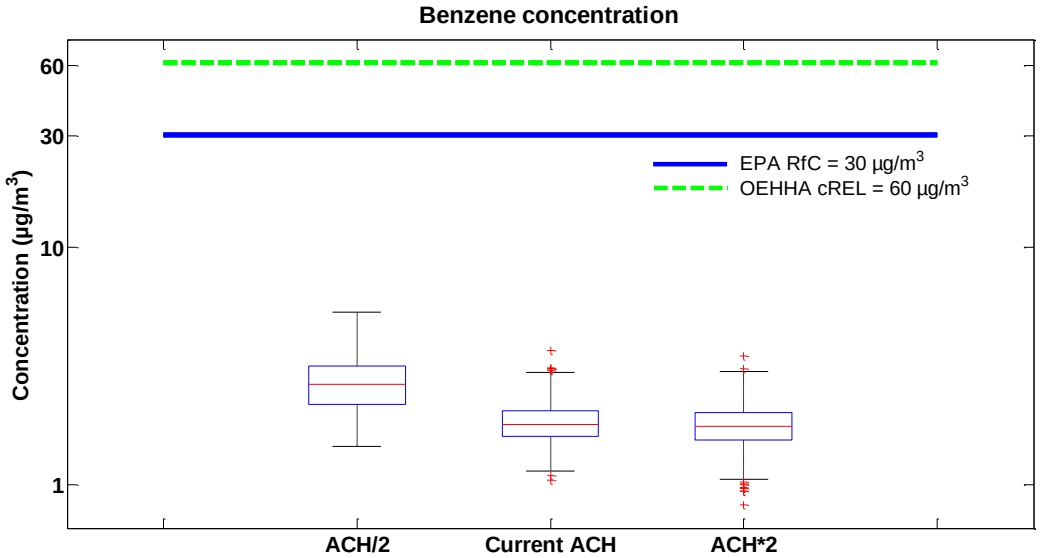

Toluene concentration
5000
300
16
10
Concentration (µg/m3)
EPA RfC = 5000 µg/m3
OEHHA cREL = 300 µg/m3
ACH/2
Current ACH
ACH*2

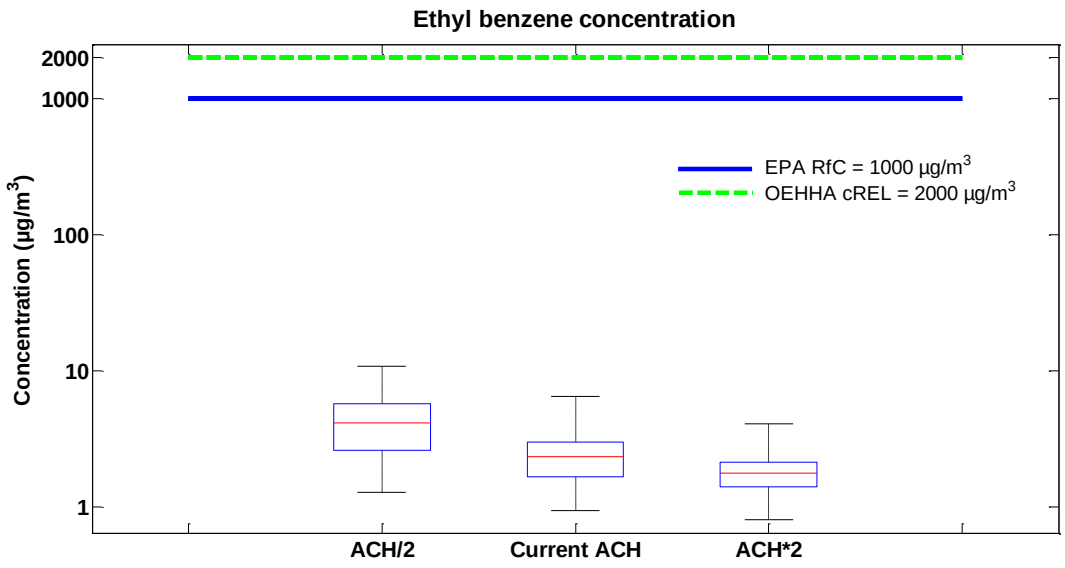

Formaldehyde concentration
30
15
9
Concentration (µg/m3)
OEHHA cREL = 9 µg/m3
ACH/2
Current ACH
ACH*2

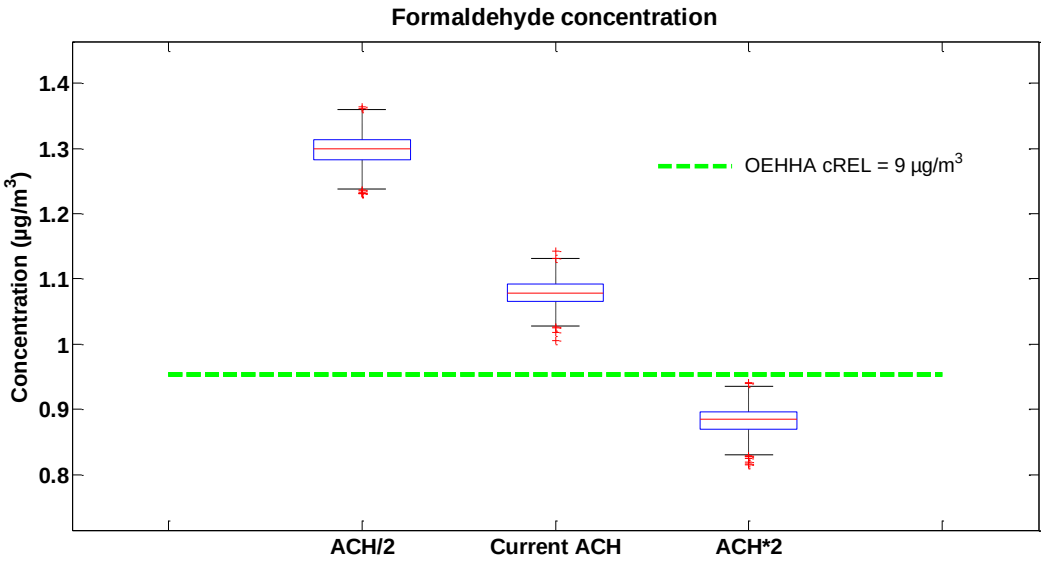

Acetaldehyde concentration
Concentration (µg/m3)
140
100
50
9
4
EPA RfC = 9 µg/m3
OEHHA cREL = 140 µg/m3
ACH/2
Current ACH
ACH*2

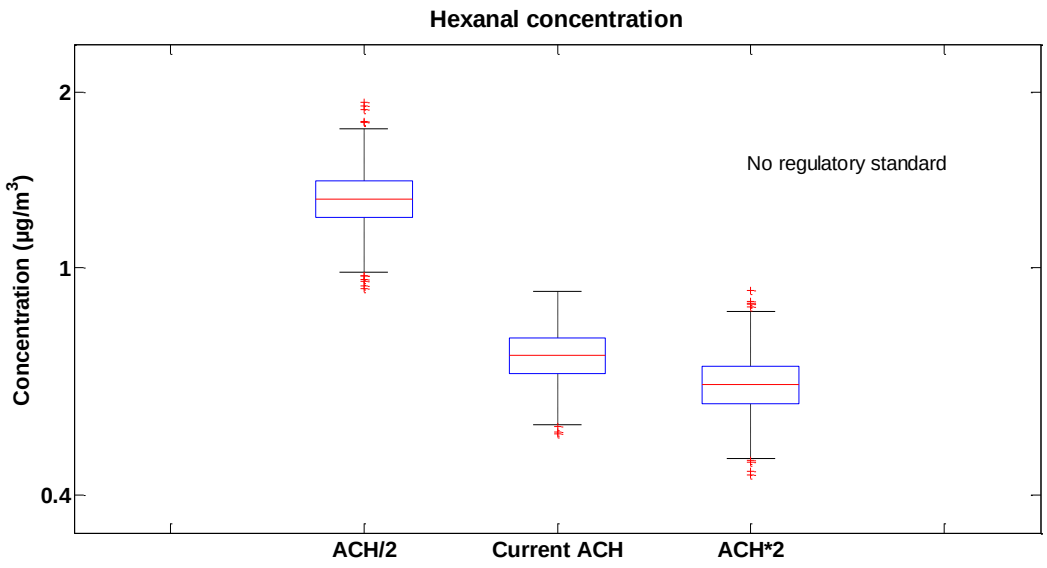
The following figures represent the concentration distributions in school buildings.

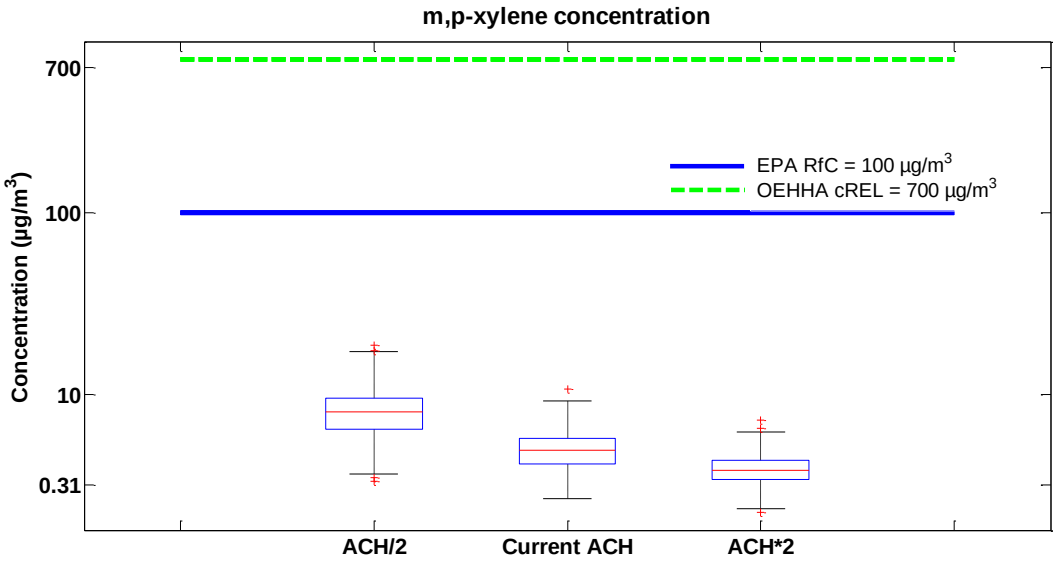


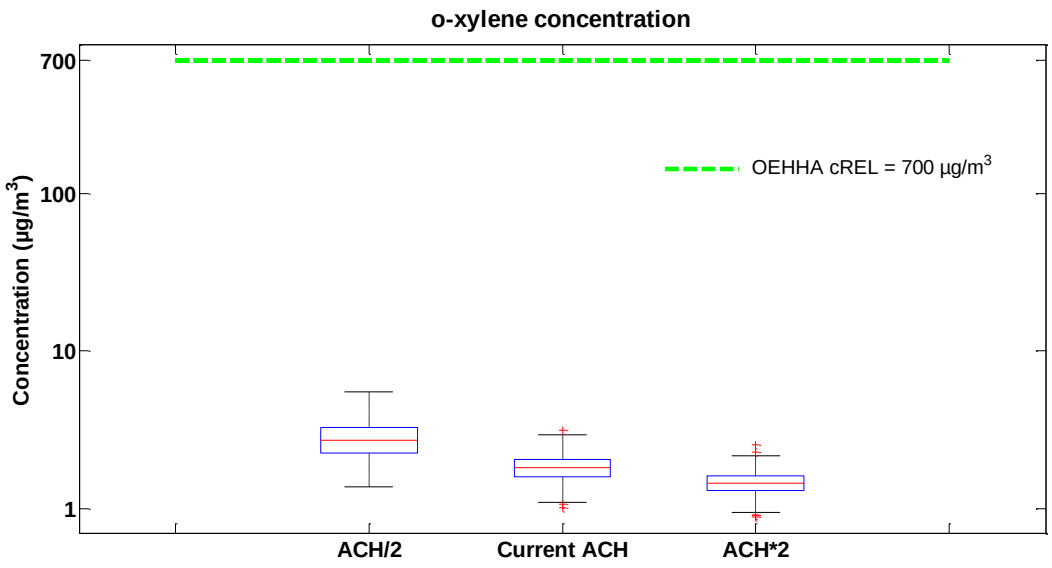


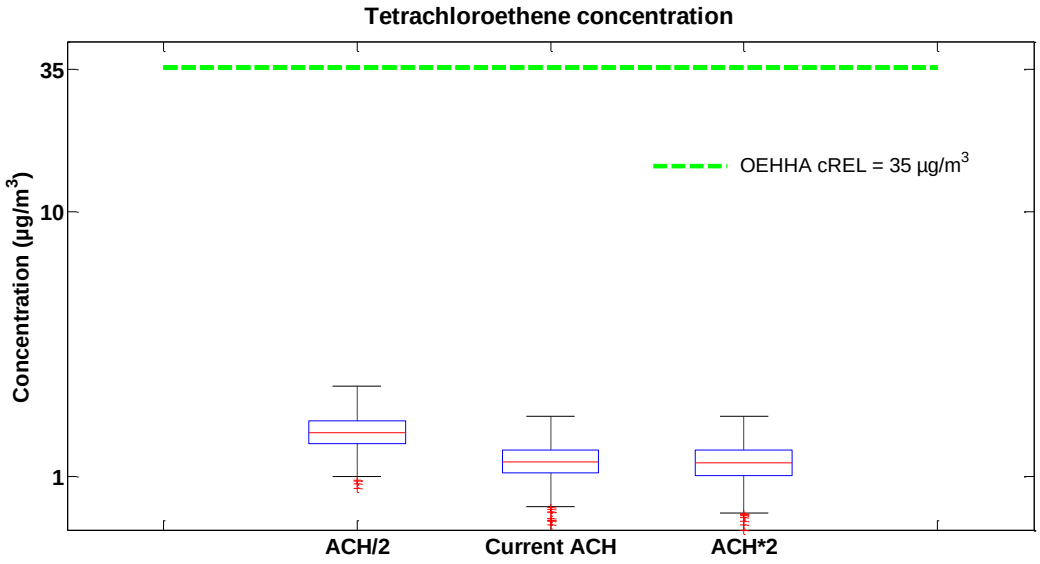

Ethyl benzene concentration
2000
1000
100
10
1
Concentration (µg/m3)
EPA RfC = 1000 µg/m3
OEHHA cREL = 2000 µg/m3
ACH/2
Current ACH
ACH*2


Formaldehyde concentration
1.4
1.3
1.2
1.1
1
0.9
0.8
Concentration (µg/m3)
OEHHA cREL = 9 µg/m3
ACH/2
Current ACH
ACH*2


Hexanal concentration
Concentration (µg/m3)
2
1
0.4
No regulatory standard
ACH/2
Current ACH
ACH*2


m,p-xylene concentration
Concentration (µg/m3)
700
100
10
0.31
EPA RfC = 100 µg/m3
OEHHA cREL = 700 µg/m3
ACH/2
Current ACH
ACH*2


o-xylene concentration
700
100
10
1
Concentration (µg/m3)
OEHHA cREL = 700 µg/m3
ACH/2
Current ACH
ACH*2


Tetrachloroethene concentration
35
10
1
Concentration (µg/m3)
OEHHA cREL = 35 µg/m3
ACH/2
Current ACH
ACH*2