Title

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Publication Date
2011-02-01

Final Report

Balancing energy conservation and occupant needs in ventilation rate standards for "Big Box" stores in California: predicted indoor air quality and energy consumption using a matrix of ventilation scenarios

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February 2011

Funds for this project came from an award by the California Institute for Energy and Environment under research contract POB229-L40 from the California Energy Commission (CEC) through their Public Interest Energy Research Program (PIER). The project was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We thank members of the Technical Advisory Committee for their time and effort in participating in our meeting and in reviewing the multiple drafts. We also thank William Fisk and Jennifer Logue for their helpful reviews of the draft manuscript.

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Abstract

Through mass-balance modeling of various ventilation scenarios that might satisfy the ASHRAE 62.1 Indoor Air Quality (IAQ) Procedure, we estimate indoor concentrations of contaminants of concern (COCs) in California "big box" stores, compare estimates to available thresholds, and for selected scenarios estimate differences in energy consumption. Findings are intended to inform decisions on adding performance-based approaches to ventilation rate (VR) standards for commercial buildings. Using multi-zone mass-balance models and available contaminant source rates, we estimated concentrations of 34 COCs for multiple ventilation scenarios: VRmin (0.04 cfm/ft^2), VRmax (0.24 cfm/ft^2), and VRmid (0.14 cfm/ft^2). We compared COC concentrations with available health, olfactory, and irritant thresholds. We estimated building energy consumption at different VRs using a previously developed EnergyPlus model. VRmax did and VRmin did not control all contaminants adequately; VRmid did so only marginally. Air cleaning and and local ventilation near strong sources both showed promise. Higher VRs increased indoor concentrations of outdoor air pollutants. Lowering VRs in big box stores in California from VRmax to VRmid would reduce total energy use by an estimated 6.6%% and energy costs by 2.5%. Reducing required VRs in California's big box stores could reduce energy use and costs, but poses challenges for health and comfort of occupants. Source removal, air cleaning, and local ventilation may be needed at reduced VRs, and even at current recommended VRs. Also, alternative ventilation strategies taking climate and season into account in ventilation schedules may provide greater energy cost savings than constant ventilation rates, while improving IAQ.

Executive Summary

Background: This report is part of a project being conducted by LBNL for the California Energy Commission on the ASHRAE 62.1-2010 Indoor Air Quality Procedure (IAQP). The overall project goal is to provide information helpful in deciding whether to include a performance-based approach as a component of a ventilation standard for commercial buildings in California. Ventilation in this document refers to the mechanical introduction of *outdoor air* into a building The current document, the third part of the project, provides estimated indoor concentrations of a selected set of contaminants of concern (COCs), and estimated energy consumption, from physical modeling of a variety of ventilation scenarios.

Methods: To model contaminants in these scenarios, we developed computer code for simple single- and multi-component multi-zone mass-balance models to investigate and track the concentration of COCs over time in a set of ventilation scenarios, each with multiple sub-scenarios or including a range of input values. Contaminant source emission rates were derived from measured source strength values in field studies of retail or other commercial buildings. Outdoor sources of contaminants were not considered except in models including selected criteria pollutants. We compared estimated concentrations of 34 COCs (after reaching steady state in most cases) with available thresholds for chronic health effects, odor, and irritant effects. For energy models, we estimated building energy consumption using EnergyPlus software and an EnergyPlus model previously developed for a specific big box retail store: a Target Store. We linked several of the contaminant analyses to energy consumption estimates, comparing energy use per scenario, along with COC levels. Scenarios used three ventilation rates (VRs), singly or in combination: VRmin (0.04 cfm/ft^2), a low rate reported as considered for use in some big box commercial buildings; VRmax (0.24 cfm/ft^2), the highest, taken from ASHRAE Standard 62.1-2007, representing the current recommended VR for commercial buildings at a default occupant density; and VRmid (0.14 cfm/ft^2), the midpoint of the minimum to maximum range.

Results: Chronic noncancer health effect thresholds were available for 21 of 34 COCs, but olfactory and irritant threshold data were available for only 14 and three, respectively. Nine COCs had OEHHA unit risk estimates for cancer. Overall, results from the contaminant models suggest that with VRmax , predicted concentrations of the COCs examined did not exceed chronic reference exposure levels (RELs) or known olfactory or irritant thresholds, or cancer risk levels exceeding $1x10^{-5}$. With VRmin, predicted concentrations of formaldehyde exceeded the chronic REL, those of octanal exceeded the olfactory threshold, and formaldehyde, benzene, and 1,4-DCB exceeded a $1x10^{-5}$ excess risk level for cancer. VRmid, halfway between these two VRs, did not produce concentrations that exceeded available chronic health, olfactory, or irritant thresholds, or the $1x10^{-5}$ level of cancer risk; however, when considering even one group of compounds, the aldehydes, as having additive effects, VRmid succeeded just marginally in staying below thresholds for chronic non-cancer health and olfactory effects. Varying VRs with lower daytime rates and higher night-time flushing did not seem promising for energy-saving while maintaining sufficiently low indoor contaminant levels. Indoor chemical reactions, to the limited extent considered here, do not seem to be an important factor for estimating indoor

concentrations, at least of formaldehyde. Consideration of the entry of outdoor air criteria pollutants was shown to be a potentially important factor in weighing costs and benefits of changed VR standards, and cleaning of these pollutants from intake air may be a necessary strategy. Air cleaning is promising as a way to allow lower VRs in conjunction with acceptably low indoor contaminant concentrations, depending on the cost and long-term feasibility and reliability of technology to remove all COCs. Local ventilation in a contained zone near strongly emitting sources of key contaminants also shows promise as a way to allow lower general VRs in areas with lower emissions; one associated challenge would be to jointly configure contents, space separation, and ventilation systems. Displacement ventilation, based on prior work, does not seem promising as a strategy to increase ventilation effectiveness in big box stores and allow reduced outdoor air VRs. The energy models estimate that, in California overall, lowering VRs in big box stores from VRmax to VRmid resulted in a $6403 dollar average saving for the ten climate zones studied, which represents a 2.51% reduction in the total energy costs. Preliminary assessments were made of alternative ventilation strategies that varied minimum ventilation rates optimized to reduce the energy required to heat or cool incoming ventilation air. The more tailored ventilation strategy, that considers both climate zone and seasonal variations, represented a win-win outcome compared to a continuous ventilation rate strategy, indicating both improved energy saving and improved IAQ.

Discussion and Conclusions: Reducing the required minimum VRs in big box stores in California has potential to produce a meaningful, if not proportionally large, reduction in energy use and energy-related costs. The challenge would be to do this in a way that protects the health and comfort of occupants of these buildings, including workers and customers. Findings from the various types of contaminant models produced in this project, combined with findings from a prior review of evidence about the adequacy of current prescriptive standards, suggest the following: The provision of ventilation rates that are marginally lower than the current prescriptive VR standards in big box stores could maintain levels of COCs below available chronic health, olfactory, and irritant thresholds for individual substances; however, consideration of the combined effects of related indoor contaminants is likely to increase the minimum VR levels required. Furthermore, the availability over time of increased information on chronic health, odor, and irritancy effects for indoor contaminants seems likely to increase the minimum VRs required. Considerations of measured health effects and acceptability of indoor air in big box stores, which will require new data collection, may further increase the minimum VRs required to achieve the requirements of ASHRAE 62.1-2010, given the parallel data already available from office buildings. Ultimately, if even current prescriptive VRs (equivalent to VRmax in this report) were shown to be inadequate for providing desired indoor air quality in commercial buildings, further increased ventilation might be neither an effective nor a feasible solution; source removal, air cleaning, and local ventilation may be the best strategies. Strategies such as these are likely to be necessary to provide the desired indoor air quality at *reduced* VRs.

Background

The Indoor Air Quality Procedure (IAQP) is a component of ASHRAE's Standard 62.1 "Ventilation for Acceptable Indoor Air Quality (ASHRAE 2010). The IAQP defines a performance-based (sets specific targets for IAQ control) as opposed to prescriptive (requires specified minimum VRs) approach for achieving acceptable indoor air in commercial buildings through the design and operation of a building and its ventilation system. The ASHRAE IAQP is not currently included in California's Title 24 Energy Standard, but this inclusion is being considered due to requests from some "big box" store companies with facilities in California. The apparent goal of the companies is for the new ventilation rate (VR) standards to allow provision of lower VRs in stores at levels that will allow, compared to current prescriptive standards, energy conservation and cost savings while still providing adequate indoor air quality.

This report is part of a project being conducted by LBNL for the California Energy Commission on the ASHRAE 62.1-2010 IAQP. The overall project goal is to provide information helpful in deciding whether to include a performance-based approach as a component of a ventilation standard for commercial buildings in California. The first part of this project reviewed what is known and has been written that is relevant to this decision about the IAQP ("Balancing energy conservation and occupant needs in VR standards for "Big Box" stores and other commercial buildings in California: Issues related to the ASHRAE 62.1 Indoor Air Quality Procedure"). A key consideration for the IAQP is the effectiveness of different VRs in controlling contaminants of concern (COCs) in indoor air, where the COCs include volatile organic compounds (VOCs) and criteria air pollutants.

The second part of this project defined input parameters for modeling a range of ventilation scenarios in order to estimate, for each scenario, the indoor concentrations of a set of COCs ("Parametric Big Box Commercial Building IAQ Matrix"). We will refer to this document as the "model input matrix." The model input matrix defined a number of scenarios to use in estimating indoor concentrations of COCs under a range of ventilation strategies (Table 1). The set of scenarios was developed to estimate COC concentrations in a "big box" retail commercial building (CB), using a variety of conditions ranging from simple to complex. These included: different VR schedules, including several fixed VRs and also differing day and night VRs; consideration of additional sources and removal of contaminants, including entrained outdoor air contaminants, byproducts of indoor chemical reactions, and use of air cleaning; and spatial ventilation strategies, including localized ventilation and displacement ventilation. (Although modeling of displacement ventilation was planned, this turned out not to be feasible and was not performed in the next phase of the project.)

The current document, the third part of the project, provides results of modeling these scenarios for indoor concentrations of contaminants, and modeling several of the scenarios for energy consumption as well. Energy conservation in big box stores has been the driver for introducing reduced ventilation rates that might be acceptable under the IAQP. To model contaminants in these scenarios, we developed and applied computer codes for mass balance modeling of contaminants in well-mixed zones to investigate and track the concentration of COCs over time in each scenario. We compare the resulting COC concentrations with threshold values, as available, for chronic non-cancer and cancer health effects, odor, and sensory effects, and identify contaminants that may be of particular concern.

In the energy consumption modeling, we estimated the potential for energy savings under selected ventilation scenarios. We modeled building energy consumption using EnergyPlus software and an EnergyPlus model previously developed to simulate Target Stores. Several of the contaminant analyses in this report have been linked to energy consumption estimates, so that energy use could be compared along with COC levels.

Although there is no universally used definition of big box retail, the State of California defines big box retail as a "store of greater than 75,000 square feet of gross buildable area that will generate sales or use tax (California Law AB 178)." Major types of big box stores and their merchandise include, by one type of categorization (Clanton et al., 2004):

- Discount department stores (80,000 – 200,000 ft^2) – wide variety of up to 60,000 distinct items.
- Category killers (20,000-120,000 ft^2) – specialty or niche items in a specific category.
- Outlet stores (20,000-80,000 ft^2) – discount items, often from major department stores.
- Warehouse clubs (104,000-170,000 ft^2) – limited variety of up to 5,000 products in bulk sizes to customers paying an annual membership fee.
- Supercenters (average 250,000 ft^2) – full grocery and retail services.

The big box store modeled in this project, a 124,000 ft^2 facility offering retail items including food service and groceries to the general public, fits into the category of Discount Department Store.

Table 1. Matrix of model inputs for estimating indoor contaminant concentrations in big box commercial buildings[a]

	Ventilation Rates Used[b]		
	VRmin	**VRmax**	**VRmid**
	0.17 ACH 0.04 cfm/ft^2	1.03 ACH 0.24 cfm/ft^2	0.60 ACH 0.14 cfm/ft^2
Scenario A: Constant VR over 24-hour period			
A1	VRmin over 24 hours		
A2		VRmax over 24 hours	
A3			VRmid over 24 hours
Scenario B: Dual (day/night) ventilation periods			
B1	VRmin (5 am to 10 pm)	VRmax (10 pm to 5 am)	
B2		VRmax (10 pm to 5 am)	VRmid (5 am to 10 pm)
Scenario C: Contaminated outdoor air[c] entering supply airstream			
C1	VRmin over 24 hours + OA		
C2		VRmax over 24 hours + OA	
C3			VRmid over 24 hours + OA entry
Scenario D: Ozone + d-limonene reaction[d]			
D1	VRmin (5 am to 10 pm)	VRmax (10 pm to 5 am)	
D2		VRmax (10 pm to 5 am)	VRmid (5 am to 10 pm)
Scenario E: Air cleaning			
E1			VRmid over 24 hours + varying filter efficiencies
Scenario F: Application of local ventilation strategies			
F1		various	
Scenario G: Application of displacement ventilation			
G1		(not modeled)	

Abbreviations: ACH, air changes per hour; VR, ventilation rate.

[a] all models assume typical whole building emission factors (WBEFs), using median WBEF, or midpoint if median not available

[b] three levels of VR used as inputs for specific sub-scenarios. The lowest, VRmin, was reported as a level considered for use in a big box retail store (Grimsrud 2009) . The highest value, VRmax, was taken from ASHRAE Standard 62.1-2007 (based on default occupant density of 15 persons/1000ft^2 and assuming 16 cfm/person). The middle value, VRmid, was the midpoint of the minimum to maximum range.

[c] considers three criteria air pollutants (NO_2, CO, and O_3); otherwise repeats Scenario A.

[d] considers products of indoor air chemistry; otherwise repeats Scenario B.

Methods

Contaminant modeling – methods

The mass balance modeling conducted for this effort uses simple single- and multi-component mass-balance models for well mixed zones. The building energy modeling uses EnergyPlus software (US DOE 2010) and a pre-existing model developed for a Target Store (LBNL 2010). Contaminant source rates were derived from measured source strength values in field studies of retail or other commercial buildings. Three VRs were used in most modeling scenarios (Table 1). The lowest, VRmin, was reported by Grimsrud et al (2009) in the U.S. as considered for use in some big box commercial buildings. The highest, VRmax, was taken from ASHRAE Standard 62.1-2010 (assumes 16 cfm/person, based on the default occupant density of 15 persons/1,000 ft^2). The middle value, VRmid, was the midpoint of the minimum to maximum range. These VRs are presented in this order throughout this paper. VRmax represents the current recommended VR for commercial buildings (at a default occupant density).

Contaminants of concern and reference exposure levels

Section 6.3 of ASHRAE Standard 62.1 (ASHRAE 2010) describes the use of the IAQP, a performance-based design approach for determination of required ventilation. Section 6.3.2 states "For each contaminant of concern, a concentration limit and its corresponding exposure period and an appropriate reference to a cognizant authority shall be specified." Appendix B of the Standard (including Tables B-1, B-2, and B-3) provides an informative summary of selected air quality guidelines. The 2010 publication of the standard, relative to the 2007 version, contains a considerable upgrade and expansion of information on contaminants of concern, and information from cognizant authorities regarding thresholds and reference exposure levels.

Table 2 includes 30 compounds included in the ASHRAE 62-1.2010 commercial building VR standard, in Appendix B, Table B-3 (ASHRAE 2010). Table 2 here includes all compounds listed in the ASHRAE 62.1 Table B-3 except t-butyl methyl ether and carbon tetrachloride.

Reference exposure levels for a list of contaminants of concern, based on levels specified by the California Office of Environmental Health Hazard Assessment (OEHHA) and the U.S. Agency for Toxic Substances and Disease Registry (ATSDR), are also shown in Table 2, primarily adapted from ASHRAE 62.1-2010 (ASHRAE 2010). The Table additionally lists odor thresholds for compounds, taken from Hodgson and Levin (2003b). Concentrations of COCs producing specified excess cancer risks over a working lifetime of exposure, shown in Table 3, were calculated from unit risk estimates (UREs) calculated by OEHHA and published as a Technical Support Document for Cancer Potency Factors (OEHHA 2009). These concentrations were estimated by dividing a specified excess cancer risk by the URE, and adjusting for exposure over work weeks (168 hours/40 hours) during a work life (45 years/70 years), relative to continuous lifetime exposure.

Table 2. 30 VOCs of potential concern. This table is adapted from Table B-3, Appendix B, in ANSI/ASHRAE Standard 62.1 (2010). Compounds in bold also appear in Table 4.

			CA OEHHA REL			ATSDR MRL			Odor[i] Thresh
Compound	**CAS No.**	**Chem. Class**[a]	**Acute**[c] **(µg/m^3)**	**8-hr**[d] **(µg/m^3)**	**Chron**[e] **(µg/m^3)**	**Acute**[f] **(ppb)**	**Interm.**[g] **(ppb)**	**Chron.**[h] **(ppb)**	**(µg/m^3)**
Acetaldehyde	75-07-0	Ald	470	300	140				343
Acrolein	107-02-8	Ald	2.5	0.7	0.35	3	0.4		
Acrylonitrile	107-13-1	Misc			5	100			
Benzene	71-43-2	Arom	1,300		60	9	6	3	
Bromomethane (methyl bromide)	74-83-9	Halo				50	50	5	
1,3-Butadiene	106-99-0	Alke			20				
2-Butanone	78-93-3	Ket	13,000						
2-Butoxyethanol	111-76-2	Gly				6,000	3,000	200	1643
Carbon disulfide	75-15-0	Misc	6,200		800			300	
Chlorobenzene	108-90-7	ClAro			1,000				
Chloroform	67-66-3	Halo	150		300	100	50	20	
1,4-Dichlorobenzene	106-46-7	ClAro			800	2,000	200	10	289
1,2-Dichloroethane (ethylene dichloride)	107-06-2	Halo						600	
Dichloromethane (methylene chloride)	75-09-2	Halo	14,000		400	600	300	300	
1,4-Dioxane	123-91-1	Ethr	3,000		3,000	2,000	1,000	1,000	
Ethylbenzene	100-41-4	Arom			2,000	10,000	700	300	
Ethylene glycol	107-21-1	Gly			400	788			
Formaldehyde	50-00-0	Ald	55	9	9	40	30	8	1067
n-Hexane	110-54-3	Alka			7,000	600			
Naphthalene	91-20-3	Arom			9			0.7	79
Phenol	108-95-2	Alc	5,800		200				423
2-Propanol (isoproponol)	67-63-0	Alc	3,200		7,000				
2-Propanone (acetone)	67-64-1	Ket				26,000	13,000	13,000	
Styrene	100-42-5	Arom	21,000		900	2,000		200	596
Tetrachloroethene	127-18-4	Halo	20,000		35	200		40	
Toluene	108-88-3	Arom	37,000		300	1,000			
1,1,1-Trichloroethane (Methyl chloroform)	71-55-6	Halo	68,000		1,000	2,000	700		
Trichloroethene (Trichloroethylene)	79-01-6	Halo			600	2,000	100		
Vinyl chloride	75-01-4	Halo	180,000			500	30		
Xylene isomers	1330-20-7	Arom	22,000		700		2,000	600	

a. **Abbreviations**: Alc = alcohol; Ethr = ether; Gly = glycol ether; Ket = ketone; Ald = aldehyde; Estr = acetates and other esters; Acid = carboxylic acid; Alka = alkane HC; Alke = alkene HC; Cycl = cyclic HC; Terp = terpene HC; Arom = aromatic HC; ClAro = chlorinated aromatic HC; Halo = halogenated aliphatic HC; Misc = miscellaneous category
c. Exposure averaging time is 1 hour
d. Exposure averaging time is 8 hours and which may be repeated
e. Designed to address continuous exposures for up to a lifetime: the exposure metric used is the annual average exposure
f. Exposure to a chemical for a duration of 14 days or less, as specified in the Toxicological Profiles
g. Exposure to a chemical for a duration of 15-364 days, as specified in the Toxicological Profiles
h. Exposure to a chemical for 365 days or more, as specified in the Toxicological Profiles.
i. Odor threshold for VOCs from Table 1 of Hodgson and Levin (2003b)

Table 3. 3. Concentrations producing specified excess cancer risks, based on OEHHA Unit Risk estimates available for compounds in Table 2 (OEHHA 2009).

Compound	OEHHA Unit Risk Estimates (UREs)	Concentration Producing Specified Excess Cancer Risk from Working Life Occupational Exposure*		
		10^{-4}	10^{-5}	10^{-6}
	$(\mu g/m^3)^{-1}$	$(\mu g/m^3)$	$(\mu g/m^3)$	$(\mu g/m^3)$
Acetaldehyde	2.7 E-6	242	24.2	2.4
Benzene	2.5 E-5	26	2.6	0.3
Chloroform	5.3 E-6	123	12.3	1.2
1,4-DCB	1.1 E-5	59	5.9	0.6
Dichloromethane	1.0 E-6	653	65.3	6.5
Ethylbenzene	2.5 E-6	261	26.1	2.6
Formaldehyde	6.0 E-6	109	10.9	1.1
Naphthalene	3.4 E-5	19	1.9	0.2
Trichloroethene	2.0 E-6	327	32.7	3.3

* concentration calculated as Excess Cancer Risk/URE * 168/40 * 70/45

VOC source inputs

The COCs initially considered for analyses here include the 30 volatile organic compounds (VOCs) shown in Table 2. Some analyses here also include three criteria air pollutants (nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO)) for which the primary source is outdoor air. We did not include particles because the usual particle filtration substantially reduces impacts of ventilation rates on indoor particle concentrations. Table 4 provides a list of VOCs and aldehydes for which both indoor concentrations and sufficient other information were provided in the few available studies to calculate whole building emission factors (WBEFs) in commercial buildings. These included 24 compounds, of the 30 COCs listed in Table 2, for which sufficient data were available to estimate WBEFs, including 23 compounds shown in bold in Table 2, and with the single listed xylene isomer disaggregated into two separate items, totaling 24. Table 4 also includes 12 additional compounds commonly found in commercial buildings for which estimated WBEFs were available from a survey of concentrations and VRs in small and medium-size commercial buildings located in California (SMCB Study) (Bennett et al. 2010).

Five studies were used to estimate WBEFs. The SMCB Study collected data on a set of indoor air contaminants, contaminant sources, and ventilation rates in a random sample of commercial buildings (retail, school, and office) in California, built between 1978 and 2005, with floor areas between 1,000 and 50,000 ft^2, and with fewer than four stories (Bennett et al. 2010). Loh et al. (2006) conducted measurements in big box retail stores (ventilation rate and floor area used were based upon 0.08 CFM/ft^2 (based on personal communication with Scott Williams of Target Stores)). Hotchi et al. (2006) measured VOCs in a Target store in the San Francisco Bay Area and calculated WBEFs. Hodgson et al (2003a) measured WBEF ($\mu g/m^2$-h) at a call center in Northern California. Hodgson and Levin (2003a) estimated maximum and central tendency concentrations from three multi-building studies of offices in the U.S. for which WBEFs could be inferred (again assuming 0.08 CFM/ft^2 of outside air). Midpoints for these analyses were calculated as the mean of the reported minimum and maximum values.

Table 5 shows, for each COC modeled in this study, the values of WBEF provided by available studies, and the single WBEF value selected as most relevant to use as input into the modeled simulations. The following categories of buildings were considered to be most relevant (listed in order of decreasing relevance): Target Big Box retail stores, big box retail stores, and commercial buildings generally including offices. The selection process involved using, if available, GM data reported by Loh et al (2006); or if not available, using the value from the next source in the following list, and so on: Hotchi et al (2006) Target Store data; SMCB (Bennett et al. 2010); Hodgson and Levin (2003a). Note that WBEFs were available and selected for all compounds listed in Table 5 except carbon disulfide and vinyl chloride.

Equation 1 was used to calculate values of WBEF. This equation assumes that the indoor contaminant concentrations measured in these studies were equilibrium values. The equation also assumes that contaminant removal from indoor air by deposition and chemical reaction was negligible relative to contaminant removal by ventilation. For contaminants with significant removal by deposition or reaction, the calculated values of WBEF are effective values equal to the total whole building emission rate minus the contaminant removal rate by deposition or reaction. This simplification was necessary given available data but leads to some errors in prediction of indoor contaminant concentrations at VRs other than those in the original studies.

Table 4. Comparison of all available (estimated and/or measured) WBEFs reviewed for 36 COCs.

Units: μg m^{-2} h^{-1}	SMCB (Bennett et al. 2010)						Loh et al. (2006)			Hotchi et al. (2006)	Hodgson and Levin (2003a)		Hodgson and Levin (2003a) Table 8	
	SMCB Retail Stores		SMCB Office Bldgs.		SMCB Retail + Office		All Stores	All Stores	Dept and MP Stores	Target store				
Compound	median	mipdoint	median	mipdoint	median	mipdoint	mipoint	median	GM mp		median	midpoint	CT	max
Acetaldehyde	6.45	11.7	14.7	12.4	12.8	12.4	52.9	17.2	11.9	28.3	12.8	14.0	0.00	0.00
Benzene	n/a	0.00	0.34	0.49	0.34	0.49	6.10	2.50	2.90	0.00	0.00	0.00	0.46	0.00
2-Butanone										5.00			n/a	3.01
2-Butoxyethanol	2.37	7.24	3.26	51.2	2.97	51.0	0.00	0.00	0.00	65.1	162	275	0.20	0.00
Carbon disulfide													n/a	2.71
Chlorobenzene													n/a	0.05
Chloroform	0.53	2.03	0.08	0.18	0.13	1.95	4.00	0.70	0.70	0.00	0.00	0.00	n/a	0.60
1,4-DCB	0.03	0.04	0.06	0.71	0.06	0.71	36.60	3.97	6.00	1.10	0.00	0.00	0.01	1.69
Dichloromethane	0.47	3.96	1.07	2.71	1.00	3.84	10.6	1.80	3.80	1.30	0.00	0.00	0.17	27.2
Ethylbenzene	0.50	0.51	0.97	1.53	0.55	1.53	78.0	4.70	6.50	0.00	0.00	0.00	0.16	0.87
Formaldehyde	37.1	39.1	24.4	28.1	25.8	33.8	67.0	28.6	21.2	45.0	84.5	73.0	0.0	0.0
n-Hexane	1.64	1.52	0.64	1.50	0.90	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.26	1.28
Naphthalene	0.24	0.32	0.27	0.36	0.26	0.36	0.00	0.00	0.00	1.00	0.00	0.00	n/a	0.53
Phenol	0.48	0.75	3.38	5.21	2.28	5.11	0.00	0.00	0.00	4.10	0.00	0.00	n/a	0.95
2-Propanol										8.10			1.36	36.7
2-Propanone	52.3	365	25.6	29.1	30.3	360	0.00	0.00	0.00	18.5	185	198	4.53	20.21
Styrene	0.29	1.07	0.72	2.56	0.70	2.56	24.2	3.10	5.00	0.00	0.00	0.00	0.14	0.41
Tetrachloroethene	0.21	0.22	0.10	7.08	0.12	7.08	37.0	1.90	2.30		0.00	0.00	0.10	0.81
Toluene	3.35	4.52	3.73	6.83	3.54	6.83	380	61.5	86.3	34.8	7.25	5.83	0.81	15.4
1,1,1-Trichloroethane										1.40			0.43	20.5
Trichloroethene	0.03	0.05	0.06	0.19	0.05	0.19	32.00	0.73	0.63	0.00	0.00	0.00	0.49	1.30
Vinyl chloride														
m/p-Xylene	1.25	1.38	2.26	3.56	1.50	3.56	1280	10.5	15.3	8.50	0.00	0.00	0.47	3.35
o-xylene	0.76	0.88	0.94	1.61	0.85	1.61	45.30	4.50	5.00	0.00	0.00	0.00	0.22	1.17
Additional compounds identified in studies not in original Matrix of Inputs														
TMPD-DIB	2.34	3.31	0.97	2.10	1.06	2.58								
TMPD-MIB		0.27	0.27	0.27	0.27									
a-pinene	1.65	4.71	2.46	3.40	2.43	4.45								
a-terpineol	0.03	0.07	0.22	2.61	0.18	2.61								
benzaldehyde	0.08	0.27	1.28	1.82	0.51	1.76				11.2			0.16	0.50
D5 siloxane	7.65	10.1	11.7	154	11.4	153				24.1			0.25	n/a
decanal	16.7	18.6	10.4	35.6	11.5	35.6								
diethylphthalate	0.73	1.22	0.32	1.62	0.34	1.62							0.00	0.11
d-limonene	9.32	7.30	3.11	100	6.54	100				8.00			0.31	3.14
hexanal	3.69	4.42	4.10	5.07	3.92	5.07				9.40			0.17	0.85
nonanal	10.5	10.1	5.29	19.3	5.94	19.3							0.13	0.35
octanal	2.70	13.0	1.51	11.9	1.65	12.4								

Abbreviations: SMCB = Small and Medium Commercial Buildings Study; GM mp = Geometric Mean Midpoint; CT = Central tendency; 1,4-DCB = 1,4-Dichlorobenzene; TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol di-isobutyrate; TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol mono-isobutyrate; D5 siloxane = decamethylcyclopentasiloxane

Table 5. Whole building emission factors for multi-purpose and department store, using published data on the midpoint of GMs for 36 compounds from Table 2 (selected values[a] in bold).

Units: $\mu g\ m^{-2}\ h^{-1}$ Compound	Loh et al. (2006) Dept & MP GM mp	Hotchi et al. (2006) Target store	SMCB (Bennett et al. 2010) SMCB Retail + Office median	mipdoint	Hodgson and Levin (2003a) Table 8 CT	max	Selected input	Reference for selected
Acetaldehyde	**11.9**	28.3	12.8	12.4	0.0	0.0	11.9	Loh et al (2006)
Benzene	**2.90**	0.00	0.34	0.49	0.46	0.00	2.90	Loh et al (2006)
2-Butanone		**5.00**			n/a	3.01	5.00	Hotchi et al (2006)
2-Butoxyethanol	0.0	**65.1**	3.0	51.0	0.2	0.0	65.1	Hotchi et al (2006)
Carbon disulfide					n/a	2.7		---
Chlorobenzene					n/a	**0.05**	0.05	Hodgson and Levin
Chloroform	**0.70**	0.00	0.13	1.95	n/a	0.60	0.70	Loh et al (2006)
1,4-DCB	**6.00**	1.10	0.06	0.71	0.01	1.69	6.00	Loh et al (2006)
Dichloromethane	**3.80**	1.30	1.00	3.84	0.17	27.2	3.80	Loh et al (2006)
Ethylbenzene	**6.50**	0.00	0.55	1.53	0.16	0.9	6.50	Loh et al (2006)
Formaldehyde	**21.2**	45.0	25.8	33.8	0.00	0.0	21.2	Loh et al (2006)
n-Hexane	0.00	0.00	**0.90**	1.50	0.26	1.3	0.90	Loh et al (2006)
Naphthalene	0.00	**1.00**	0.26	0.36	n/a	0.5	1.00	SMCB
Phenol	0.00	**4.10**	2.28	5.11	n/a	0.9	4.10	Hotchi et al (2006)
2-Propanol		**8.1**			1.4	36.7	8.10	Hotchi et al (2006)
2-Propanone	0.0	**18.5**	30.3	360	4.5	20.2	18.5	Hotchi et al (2006)
Styrene	**5.0**	0.0	0.7	2.6	0.1	0.4	5.00	Hotchi et al (2006)
Tetrachloroethene	**2.3**		0.1	7.1	0.1	0.8	2.30	Loh et al (2006)
Toluene	**86.3**	34.8	3.5	6.8	0.8	15.4	86.3	Loh et al (2006)
1,1,1-Trichloroethane		**1.40**			0.4	20.5	1.40	Loh et al (2006)
Trichloroethene	**0.63**	0.0	0.0	0.2	0.5	1.3	0.63	Loh et al (2006)
Vinyl chloride								---
m/p-Xylene	**15.3**	8.5	1.5	3.6	0.5	3.3	15.3	Loh et al (2006)
o-xylene	**5.0**	0.0	0.8	1.6	0.2	1.2	5.0	Loh et al (2006)
Additional compounds identified in studies not in original Matrix of Inputs								
TMPD-DIB			**1.06**	2.6			1.06	SMCB
TMPD-MIB			**0.27**	0.3			0.27	SMCB
a-pinene			**2.43**	4.5			2.43	SMCB
a-terpineol			**0.18**	2.6			0.18	SMCB
benzaldehyde		**11.2**	0.5	1.8	0.2	0.5	11.2	Hotchi et al (2006)
D5 siloxane		**24.1**	11.4	153	0.2	n/a	24.1	Hotchi et al (2006)
decanal			**11.5**	35.6			11.5	SMCB
diethylphthalate			**0.34**	1.6	0.0	0.1	0.34	SMCB
d-limonene		**8.0**	6.5	100	0.3	3.1	8.00	Hotchi et al (2006)
hexanal		**9.4**	3.9	5.1	0.2	0.9	9.40	Hotchi et al (2006)
nonanal			**5.94**	19.3	0.1	0.4	5.94	SMCB
octanal			**1.65**	12.4			1.65	SMCB

Abbreviations: SMCB = Small and Medium Commercial Buildings Study; GM mp = Geometric Mean Midpoint; CT = Central tendency; 1,4-DCB = 1,4-Dichlorobenzene; TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol di-isobutyrate; TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol mono-isobutyrate; D5 siloxane = decamethylcyclopentasiloxane

[a] used GM data reported by Loh et al (2006), and if not available from that source, then taken from the next source in the following list, and so on: Hotchi et al (2006) Target Store data; SMCB (Bennett et al. 2010); Hodgson and Levin (2003).

Emission factors (E) for each compound, in µg m^{-2} h^{-1} were calculated as in Equation 1:

$$E = C_{ss} * Q / A \qquad [1]$$

where

E = emission factor equal to total emission rate divided by floor area,
C_{ss} = equilibrium indoor contaminant concentration (µg m^{-3}),
Q = outdoor ventilation supply rate (m^3 h^{-1}), and
A = floor area of the commercial building space under study (m^2).

Criteria Pollutant Inputs

Only scenario C (see Table 1) required as inputs the concentrations of criteria pollutants of ambient origin (O_3, NO_2, and CO). For these models, we selected one northern and one southern California city, and obtained data from ambient air quality monitoring stations in Sacramento and Los Angeles (Table 6). These data were downloaded from the U.S. EPA's ambient air quality data websites:

http://oaspub.epa.gov/aqspub2/AQS_Annsum.AnnualSummary and
http://www.epa.gov/air/data/monvals.html?st~CA~California.

We extracted four sets of seasonal data to use as inputs for the models. Each set of seasonal data included a two-week period, with the mid-point of each period at either the vernal equinox, autumnal equinox, summer solstice, or winter solstice. For each period, we extracted 1-hr averages for O_3, NO_2, and CO. The median values of these 1-hr means for the three criteria pollutants for the two locations and for two years are provided in Table 6.

Table 6. The median of the mean annual 1-hour concentrations (2008 and 2009) measured among monitors in Sacramento and Los Angeles (USEPA 2010)

	2008				2009					NAAQS
	Sacramento		Los Angeles		Sacramento		Los Angeles			(1-hr)
	Median	Site ID	Median	Site ID	Median	Site ID	Median	Site ID		
NO_2 (ppm)	0.0108	60670 00642 60201	0.23	603700 024260 202	0.0096	60670 00242 60201	0.0184	60371 30242 60201		0.10 ppm
CO (ppm)	0.38	60670 00642 10101	0.5	603716 024210 101	0.34	60670 01442 10101	0.37	60370 11342 10101		35 ppm
O_3 (ppm)	0.05	60670 00644 20101	0.052	603720 054420 101	0.05	60670 00244 20101	0.055	60372 00544 20101		0.12 ppm

Model for Pollutant Dispersion

We applied a first-order well-mixed-zone model to predict indoor air quality. In the model, the building is divided into regions, or zones, within which the indoor air contaminant concentration is assumed to be well-mixed, effectively, at any instance in time. Mathematically, the mass-balance is written for zone i as Equation (2):

$$V_i \frac{dC_i}{dt} = S_i + \sum_{j=0}^{J} C_j F_{ji} - C_i\left(\sum_{j=0}^{J} F_{ij} - \lambda V_i\right) \qquad (2)$$

where

J is the number of zones making up the building;
V is volume [m^3]; C is concentration [$\mu g/m^3$];
S is the emission rate [$\mu g/h$];
F_{ji} is volumetric flow rate from zone j to zone i [m^3/h]; and
λ is the first-order decay [1/h].

Equation (2) is written for all indoor zones, and can reflect flow from an outside zone at a specified concentration. The system of equations is solved using an analytical or numerical solution scheme; we use the lsoda solver which is contained in the deSolve package in the R statistical software package (www.r-project.org). This kind of modeling has a number of limitations. As mentioned above, the model assumes first-order transport processes are the primary mode of transport and that contaminants mix instantaneously in a room. Aerosol transport, gas sorption and desorption processes, and particle filtration through cracks and ductwork, are not included in the model. The model also assumes the gas is neutrally buoyant and that humidity does not affect transport. Models did not consider outside air as a source of contaminants, except for the models that looked at three ambient criteria pollutants.

Ventilation scenarios and specific modeling approaches

The scenarios in the matrix of model inputs, A through F, each with multiple sub-scenarios, in the matrix of model inputs are described briefly in Table 1. Scenario A includes several constant VRs. Scenario B includes differing day and night VRs. Scenario C is like A, but with the additional consideration of the entry of outdoor pollutants. Scenario D is like B, but with the additional consideration of formaldehyde production from reaction of indoor d-limonene with entry of outdoor ozone. Scenario E includes one fixed VR, with air cleaning at different levels of efficiency for pollutant removal in the air cleaner. Scenario F includes spatial variations on local ventilation strategies for strong indoor sources. Scenario G involves displacement ventilation. The modeling approaches for these scenarios and sub-scenarios are described in more detail below, with related equations provided in Table 7.

Table 7. Equations for ventilation scenarios A through F

Scenario	Equation
A, B	$dC/dt = (S1 - C_{t-1} * F10) / V$ [3] where S1 = emission rate (µg/h), C_{t-1} = concentration from the previous time step (µg/m^3), F10 = air change rate (m^3/h), and V = volume (m^3)
A, B	$dC/dt = WBEF / height - C*F_{10} / V$ (4) where: WBEF is the whole-building emission factor [ug/m^2-h], F_{10} is the indoor to outdoor volumetric flow rate [m^3/h], and height of building assumed to be 4.2 m.
C	$dC/dt = (S1 + C0*F01 - C_{t-1}*F10) / V - C_{t-1}*L1$ [5] where S1 = emission rate (µg/h), C0 = outdoor concentration (µg/m^3), F01 = outdoor to indoor air change rate (m^3/h), C_{t-1} = concentration from the previous time step (µg/m^3), F10 = indoor to outdoor air change rate (m^3/h), V = volume (m^3), and L1 = decay rate (h^{-1}).
	$dL/dt = k_L - k_R[O_3][L]$ [6] $dO_3/dt = \alpha\lambda - k_R[O_3][L]$ [7] $dF/dt = k_F + yk_R[O_3][L]$ [8] where: L = d-limonene concentration, O_3 = ozone concentration, F = formaldehyde concentration, k_L = reaction rate for d-limonene, k_R = reaction rate for, k_F = reaction rate for formaldehyde, α = ozone penetration, λ = air change rate, and y = reaction yield.
D	$L(t) = [L] + dL(t-1)$ [9]

	$$dF = [O_3] * L(t) * y * k_R * 3600 \quad [10]$$ $$F(t) = [F] + dF \quad [11]$$ $$dL(t) = -[O_3] * L(t) * k_R * 3600 \quad [12]$$ where [L] = concentration of d-limonene from indoor source ($\mu g/m^3$), $[O_3]$ = concentration of indoor ozone ($\mu g/m^3$), [F] = concentration of formaldehyde from indoor source ($\mu g/m^3$), y = reaction yield (0.28), k_R = formaldehyde reaction rate (8.8×10^{-5} $m^3/\mu g/sec$), L(t) = d-limonene from indoor source + d-limonene left over from the last ozone reaction, dF = formaldehyde generated from d-limonene – ozone reaction, F(t) = formaldehyde from indoor source + formaldehyde generated from d-limonene – ozone reaction, and dL(t) = amount of d-limonene left over from the reaction.
F	$$dC1/dt = (S1 + C2*F21 - C1_{t-1}*(F10 + F12)) / V \quad [13]$$ $$dC2/dt = (S2 + C1*F12 - C2_{t-1}*(F20 + F21)) / V \quad [14]$$ where C1 = Indoor chemical concentration in zone 1 ($\mu g/m^3$) C2 = Indoor chemical concentration in zone 2 ($\mu g/m^3$) S1 = Emission factor for zone 1 ($\mu g/h$) S2 = Emission factor for zone 2 ($\mu g/h$) F01 = Outdoor to zone 1 air change rate (m^3/h) F10 = Zone 1 to outdoor change rate (m^3/h) F12 = Zone 1 to zone 2 air change rate (m^3/h) F21 = Zone 2 to zone 1 air change rate (m^3/h) F20 = Zone 2 to outdoor air change rate (m^3/h) and F02 = Outdoor to zone 2 air change rate (m^3/h).

Scenario A: Constant ventilation rates

Models estimated the indoor concentration of 35 VOCs using static (time-invariant) ventilation rates over a 24-hour period, after indoor concentrations have reached steady-state levels. Three sub-scenarios each used different constant ventilation rates (Table 1):

A1. VRmin
A2. VRmax
A3. VRmid

Figure 1 depicts the models for Scenario A (and B).

Approach: We developed a single-zone model for a typical box-type retail building. We assumed no reactive decay or depositional loss of contaminants and no contaminants present in outdoor air.

Indoor concentration C (µg/m^3) at any time t was calculated by solving the differential equation [3] (Table 7).

Equation 2 reduces to equation 3, which further reduces to equation 4 (Table 6).

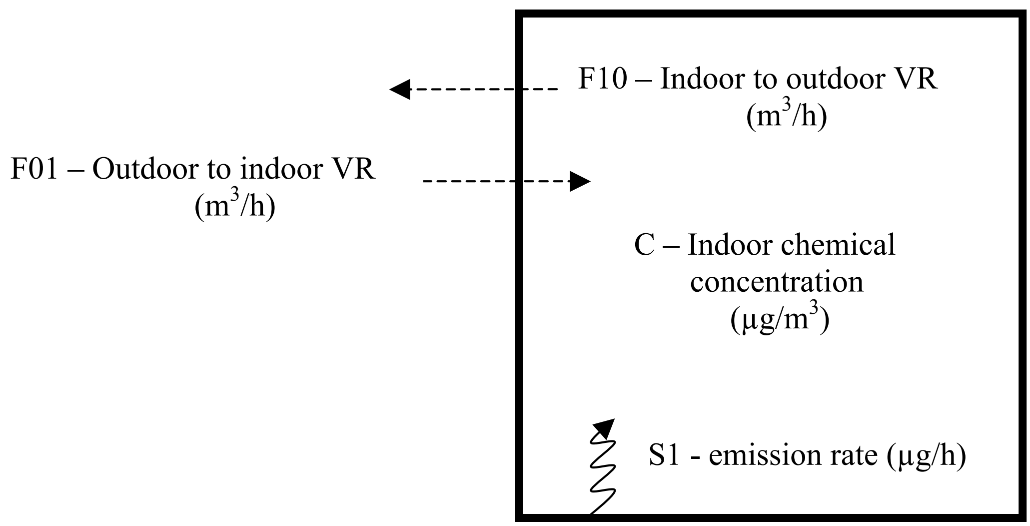


Figure 1. Modeling approach for Scenarios A and B

Scenario B: Differing day-time and night-time ventilation rates

Models estimated the indoor concentration of 34 VOCs over a 24-hour period, after indoor concentrations have reached steady-state levels, with different day-time and night-time ventilation rates. Two ventilation sub-scenarios were used:

B1. VRmin (5 AM to 10 PM), VRmax (10 PM to 5 AM)
B2. VRmid (5 AM to 10 PM), VRmax (10 PM to 5 AM)

In these models, VRmax was used only during the night in order to . . . was *Approach:* We calculated indoor concentrations in the same way as in scenario A (see Figure 1) using VRs for Scenario B shown in Table 1.

Scenario C: Considering outdoor air criteria pollutants

Models estimated the indoor concentration of NO_2, CO, and O_3 resulting from indoor sources and outdoor air infiltration. This scenario introduces three criteria air pollutants (NO_2, CO, and O_3) into the model. The outdoor air pollutant concentrations were based on data recorded in

2007 from two locations: Los Angeles and Sacramento (for details of data extraction, see Appendix 1).

Approach: Indoor concentration estimates of the three criteria air pollutants were based on the measured outdoor concentration data at the two locations during each of the four seasons, an estimated indoor contaminant decay rate (which accounts for depositional and chemical reaction losses) for each chemical (0.7 h^{-1} for NO_2; 0.0 h^{-1} for CO; and 3.6 h^{-1} for O_3) taken from the literature (Weschler 2000; Weschler et al. 1994), and the three ventilation rates:

C1. VRmin
C2. VRmax
C3. VRmid

The indoor concentration C (μg/m^3) of each of the three criteria pollutants at any time t was calculated by solving the differential equation [5] (Table 7). See Figure 2. We used one-hour outdoor contaminant concentrations from 2007 (Spring – 3/13/2007 to 3/28/2007; Summer – 6/14/2007 to 6/29/2007; Fall – 9/16/2007 to 10/1/2007; Winter – 12/15/2007 to 12/30/2007). Missing values in the data record were replaced as described in Appendix 1. Modeling was done for each outdoor air pollutant, for each two-week period, assuming that starting indoor concentrations equaled outdoor concentrations at that time. Due to uncertainty about the true initial indoor concentration, the first 48 hours of output for each two week model was excluded.

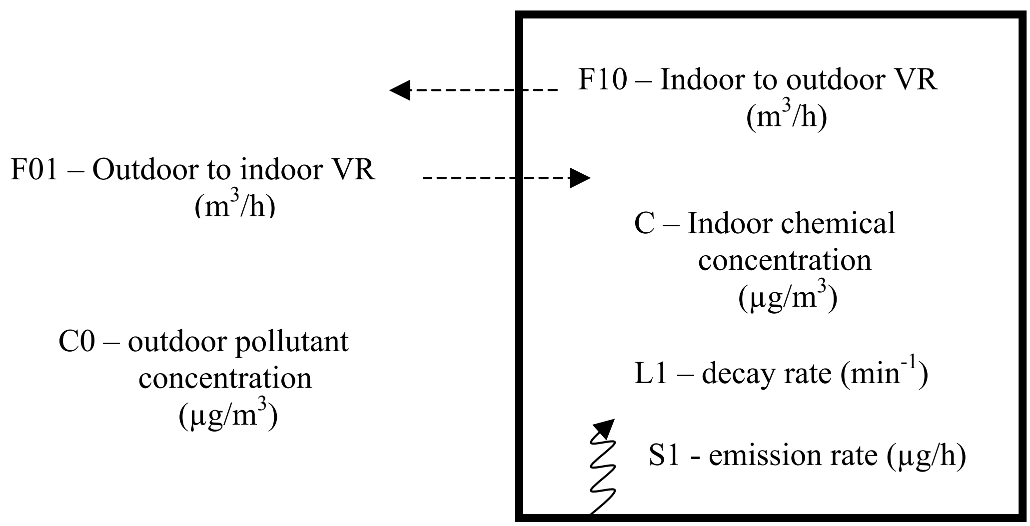


Figure 2. Modeling approach for Scenario C.

Scenario D: Ozone + d-Limonene reaction

Models estimated indoor formaldehyde concentrations, considering that formaldehyde indoors results from indoor sources, outdoor-to-indoor transport of ozone, and indoor formation from the ozone + d-limonene indoor reactions. (Note – models did not consider outside air as a source of formaldehyde.) See Figure 3. This scenario was simulated in two sub-scenarios with the same two ventilation regimes as in Scenario B:

D1. VRmin (5 AM to 10 PM), VRmax (10 PM to 5 AM)

D2. VRmid (5 AM to 10 PM), VRmax (10 PM to 5 AM)

Approach: The model used to estimate the indoor concentration of formaldehyde was rerun with an added input for additional formaldehyde produced by ozone + d-limonene reaction. The indoor formaldehyde concentration including the additional formaldehyde generated from the ozone + d-limonene reaction was modeled using the outputs from (1) the emission of d-limonene from an indoor source, (2) the emission of formaldehyde from an indoor source, and (3) the estimated amount of indoor ozone coming from outdoors for each of the two locations and the four seasons. Formaldehyde concentrations in outdoor air were not considered.

The ozone + d-limonene reactions are described in equations 6, 7, and 8 (Weschler 2000) (Table 7). We can reduce equations 6, 7, and 8, assuming that formaldehyde formation is at equilibrium over a one-hour interval. The indoor formaldehyde concentration with the additional formaldehyde generated from the ozone + d-limonene reaction was calculated at each hourly time step using equations 9, 10, 11, and 12 (Table 7). Data presented are from periods after formaldehyde concentrations from indoor emissions reached steady state levels.

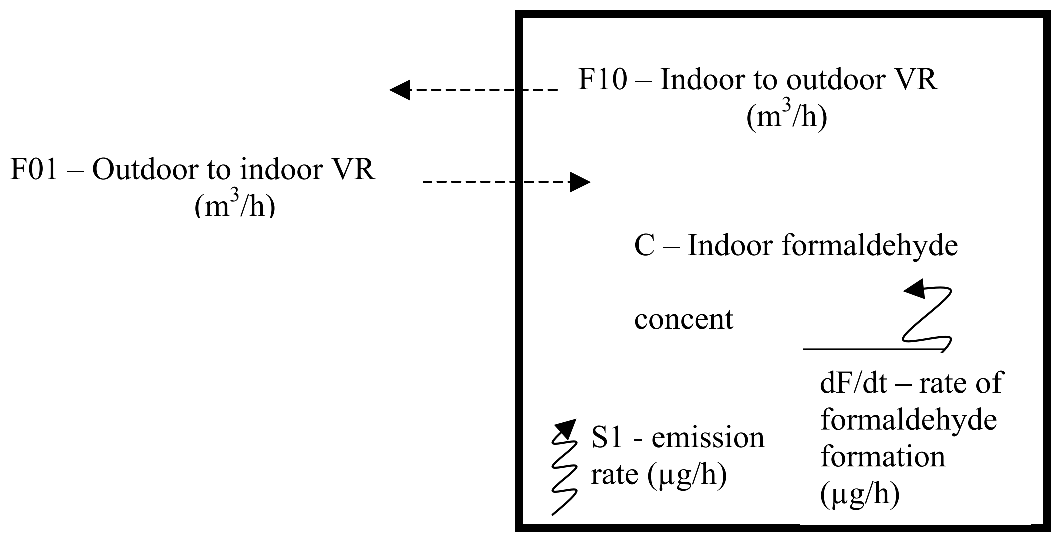


Figure 3. Modeling approach for Scenario D

Scenario E: Air cleaning

Models estimated indoor contaminant concentrations, considered effects of removal of indoor contaminants by air cleaning over a broad range of contaminant removal efficiencies in the air cleaner, in conjunction with VRmid over 24 hours. See Figure 4. Models included a coefficient zeta representing the "pollutant penetration" (proportion of contaminant passed through) for the air cleaner. Pass-through equals (1-Θ), where Θ is the removal efficiency of a filter.

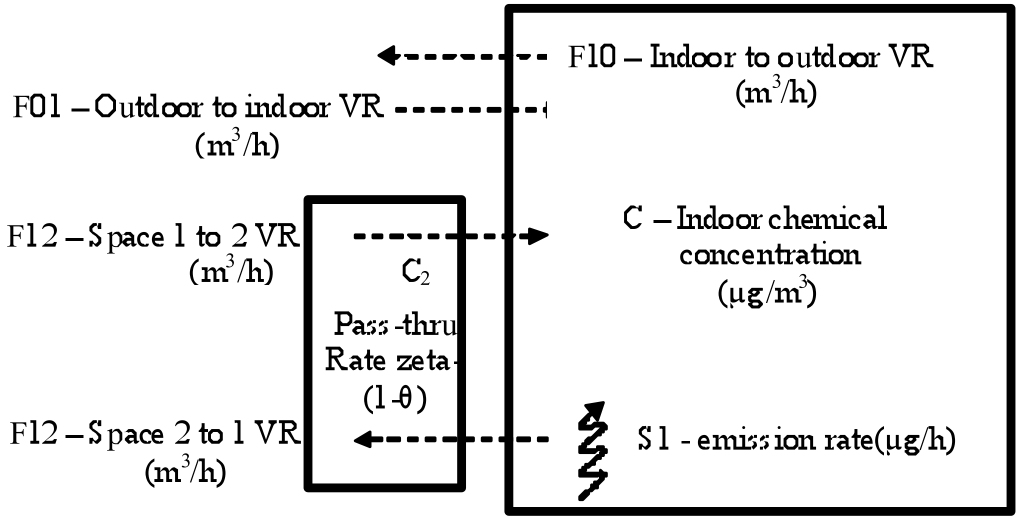


Figure 4. Modeling approach for Scenario E

Scenario F: Application of local ventilation strategies with 2-zones separated by an air curtain

Models estimated indoor contaminant concentrations in two zones, separated by an air curtain, whose volumes add up to that of the single zone used in the previous scenarios. Zone 1 contained 25% of the original retail floor and zone 2 contained 75%. (An air curtain is created by downward-directed jets of air, reaching from fans in the ceiling to intakes in the floor, to separate air in the two zones and reduce air mixing between them.)

For each contaminant, emission factors were adjusted for each zone so that the emission factor of the smaller zone was 10 times that of the larger zone, but the average across both zones was equal to the original value. We considered a somewhat extreme situation for purposes of demonstration. See Figure 5.

The indoor concentrations C1 or C2 at any time t were estimated by solving the differential equations [13] and [14] (Table 7). Reported and plotted values are for the time after steady state concentrations of indoor contaminants have been reached. The model used six different air change rates between the two zones (0.01, 0.1, 1, 2, 5, and 10 ACH of the smaller zone, zone 1) and also simulated the effects of exhausting air from the smaller zone to the outside. We plotted concentrations in zone 1 and 2 for various transfer flows, as a function of the ratio f10 / [f12+f20].

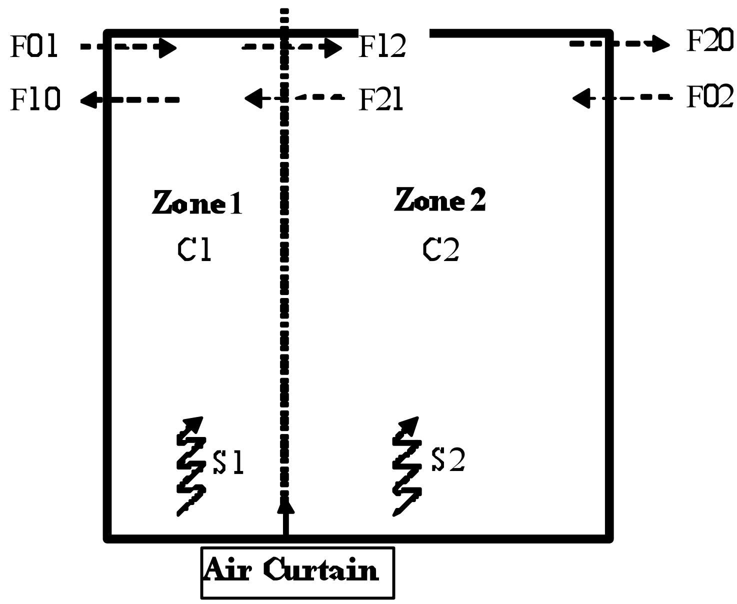


Figure 5. Modeling approach for Scenario F

Scenario G: Displacement ventilation

The Model Input Matrix specified a set of models to simulate the potential use of displacement ventilation for Big Box Retail Stores. Displacement ventilation (DV) seemed a promising subject for modeling due to its potential to provide greater ventilation efficiency than a conventional mixed ventilation strategy. ASHRAE 62.1 Section 6.2.2.2 considers the *zone air distribution effectiveness,* E_z, the effectiveness of a ventilation air distribution system at delivering ventilation air to the breathing zone of the occupant. Traditional mixed air systems used in large single story buildings have ceiling air supply diffusers and return registers used with rooftop package units. These have cooling mode E_z values of 1 and heating mode E_z ranging from 0.8 to 1, depending on the diffuser design, air discharge velocities, and ceiling height. DV, by comparison, can provide cooling E_z values of 1.2, an effective indoor air quality boost of 20% if the ventilation rate is unchanged, making the mode attractive for balancing energy and IAQ needs. Furthermore, displacement ventilation is particularly effective in spaces with ceiling heights greater than 3 meters (ASHRAE 2009). These were the primary reasons for initial consideration of displacement ventilation as a potential option for an alternative ventilation strategy for Big Box stores.

DV has been shown to be effective in office settings and classrooms, conference rooms, theaters, and other spaces in Asia, Europe, and the United States (Emmerich and McDowell, 2005; ASHRAE, 2009). Common to these conditioned spaces is that the occupants are primarily sedentary for long periods relative to the time spent in motion. As described by Emmerich and McDowell (2005),

> "The key performance issue for successful DV application is unidirectional flow and the establishment of a stable thermal stratification layer within the zone."

These authors further say that the desired goal of

> "DV system operation is stratification leading to two stable zones - a cooler, cleaner zone ending at a boundary somewhere above the occupant breathing zone and a warmer, more contaminated zone above the boundary. Plumes from occupants and other heat sources effectively transport both heat and contaminants from the lower zone to the upper zone."

In DV, the fresh ventilation air is injected at slightly cooler than room temperature and at low velocity into the floor region in the occupied space. The cooler, clean air is swept up around warm bodies/objects, human or otherwise, in a convective plume. The layout of relatively sedentary occupants in offices, classrooms, etc. is conducive to development of these stable thermal plumes.

Again from Emmerich and McDowell (2005):

> "Contaminants from sources not associated with heat generation may not be transported out of the lower zone effectively, as most research has focused on measuring or predicting concentrations of carbon dioxide (CO_2) or other passive tracer gases collocated with heat sources. Stable stratification may also not be established due to occupant activity or the distribution of heat sources or sinks."

Thus, air contaminants from indoor sources in a Big Box Retail store may not be effectively removed with the occupant generated plumes, instead being left to concentrate in the lower air space containing the occupants. Further, as the occupants move about the store, their personal convective plumes are likely disrupted, breaking the flow of ventilation air from the floor towards the ceiling. At this point the occupant would encounter the higher concentrations of contaminants from indoor emissions in the air mass not involved in the thermal displacement, possibly increasing exposures. As the complexities of modeling these phenomena adequately seemed beyond the scope of this project, we did not model the benefits of DV for big box retail spaces.

Energy Modeling Methods

The objective of this section is to quantify the impact of varying outdoor air ventilation rates on the heating and cooling energy use of a big box retail store. Building energy use simulation was performed using a previously developed EnergyPlus model of a Target store located in Pasadena, CA (Haves et al. 2008). Comparisons were made of the energy required to heat and cool the building, over a range of different ventilation scenarios, and for ten cities, each representative of a California climate zone.

Target store model

The model is based on a specific, recently constructed store, which adhered closely to a standard store design at the time of construction, identified as a "P-Store" type building. The 124,000 square foot, single story building contains retail sales floor, stock storage, and back office areas. The retail sales area includes a food service component and a grocery component that includes predominantly enclosed refrigerator cases. Figure 6 is an image of the P-Store model used.

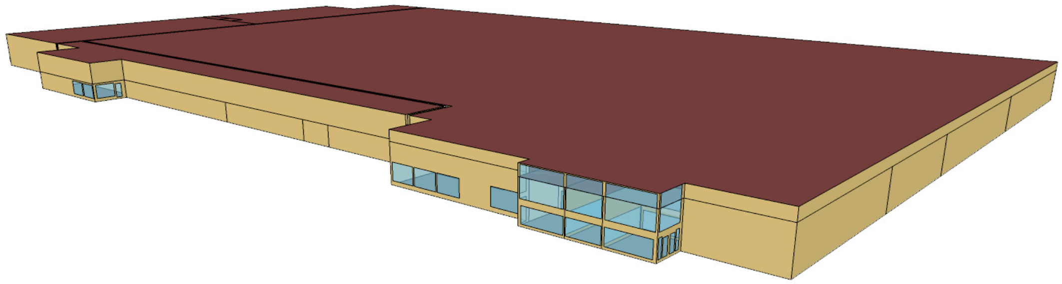


Figure 6. Target store model

The HVAC system used in the store model is a set of sixteen individual commercial rooftop constant-air-volume direct expansion (DX) cooling units, with natural gas heat. Independent compressor/condenser units located on the roof provide grocery refrigeration cooling. Table 8 describes the rooftop DX units servicing the whole building and those specific to the retail floor area.

Table 8. Summary of modeled roof top units.

	Retail Floor	Whole Building
Number of RTUs	13	16
Total Rated Capacity	237 tons	307 tons
Total Rated Air Flow Rate	88,7000 CFM	115,200 CFM
Total Supply Air Flow Rate	82,720 CFM	104,880 CFM

A breakdown of major electricity usage that does not vary with climate is shown in Table 9; this table does not include the approximately 83 mWh for parking lot lighting. Within the retail floor area, the annual electrical equipment usage breakdown includes 23 mWh for refrigerator cases, 57.0 mWh for food preparation, 46.1 mWh for checkout lanes, and the remainder used by miscellaneous equipment.

Table 9. Annual total mWh for fixed energy use

	Retail Floor	Whole Building
Lighting	826 mWh	931 mWh
Equipment	233 mWh	315 mWh

Model validation

The Target building model used in this study was based on the model previously benchmarked by Haves et al. (2008). The Haves et al. Target model was based on a standard Target store design identified as a P-Store type. The model used in this study differed significantly from the

Haves P-Store model only in extending the provision of mechanical ventilation throughout the night, in keeping with current practice.

The Haves et al. study compared the measured energy performance of seven recently constructed stores that strictly adhered to a standard P-Store design to simulation results based on the P-Store model. Simulations were performed using weather files geographically local to the corresponding measured store. The Target store model schedules, HVAC system specification, predicted store occupancy, envelope performance and internal loads were based on a combination of data provided from Target and commonly used model assumptions. Store infiltration rates were assumed to be negligible as a result of the continuous positive pressurization of the store.

The results of the energy benchmarking comparisons between simulated and measured stores indicated that, averaged over the seven stores, the model was under-predicting the electrical consumption by 1.4% and over-predicting the gas consumption by 0.7%. These results were considered sufficiently accurate to conclude that the model captured the P-Store design energy behavior.

Simulation method

Annual building simulations were performed for each ventilation scenario in the 10 different California climate zones shown in Table 10, chosen for their geographic (Figure 7, CEC 2008) and climatic diversity.

Table 10. Heating and Cooling Degree Days for Modeled Climate Zones (DOE 2010)

Zone Number	Major City	10°C baseline Heating /Cooling Degree Days	18°C baseline Heating /Cooling Degree Days
1	Arcata	151/887	2185/0
3	Oakland	45/1555	1438/28
7	San Diego	0/2506	718/304
9	Pasadena	2/2742	756/575
10	Riverside	43/2790	930/757
11	Red Bluff	249/2446	1505/782
12	Sacramento	198/2117	1486/484
13	Fresno	161/2965	1243/1127
15	El Centro	8/4750	486/2309
16	Mount Shasta	1049/1124	3008/162

Figure 7. Map of California Building Climate Zones

Ventilation scenarios

As in the previously defined contaminant models (Table 1), the minimum (VRmin), midpoint (VRmid), and maximum (VRmax) outdoor air flow rates were set at 0.04, 0.14, and 0.24 cfm/ft^2 (0.17, 0.60 and 1.03), respectively. In total, seven scenarios, detailed in Table 11, were assessed.

Table 11. Ventilation scenarios

Scenario A: Constant VR over 24-hour period			
A1	VRmin over 24 hours		
A2		VRmax over 24 hours	
A3			VRmid over 24 hours
Scenario B: Dual (day/night) ventilation periods			
B1	VRmin (5 am to 10 pm)	VRmax (10 pm to 5 am)	
B2		VRmax (10 pm to 5 am)	VRmid (5 am to 10 pm)
B1B	VRmin (10 pm to 5 am)	VRmax (5 am to 10 pm)	
B2B		VRmax (5 am to 10 pm)	VRmid (10 pm to 5 am)

As described earlier, the VRmax ventilation rate is based on the prescriptive ASHRAE 62.1 VR procedure (ASHRAE 2007) for a retail space, VRmin is a rate reportedly being used in some big box retail stores based on an IAQ procedure study (Grimsrud et al 2009). VRmid rate is the midpoint between the VRmax and VRmin rate.

Heating set points during day-time operation of the store (5 am to 10 pm) were set to 21° C (70° F). During night-time store operations, heating set points were set to 15.6° C (60° F). Cooling set points were set to 23.3° C (74° F) during day-time operation and 27.8° C (82° F) at all other times. It was anticipated that savings in cooling energy could be achieved by reducing ventilation rates during summer daytime periods. Conversely, savings in heating energy were expected by reducing night-time ventilation rates during cold winter nights. Scenarios B1 and B2 schedule reduced daytime ventilation rates during the daytime compared to the prescribed VRmax rate. Scenarios B1B and B2B reduce night-time ventilation rates from the VRmax rate.

Results

Contaminant Modeling

Scenario A – Constant ventilation rates

Table 12 provides modeled steady state (SS) concentrations(C) in indoor air of 34 COCs for each of the three sub-scenarios A1, A2, and A3, with steady ventilation rates VRmin, VRmax, and VRmid (see Table 1 for VR levels). The COCs listed in Table 12 include all COCs from Table 5 except carbon disulfide and vinyl choride, for which insufficient data were available. In all ventilation rate scenarios, for all VOCs, the following was true**:**

$$C_{24HAmin} > C_{24HAmid} > C_{24HAmax}$$
$$C_{SSmin} > C_{SSmid} > C_{SSmax}$$

Table 12 also shows that ratios of the *equilibrium* indoor air concentrations of COCs at VRmin relative to VRmax were in a narrow range from 5.8-6.2, with a mean of 5.9. The difference in steady-state concentration of formaldehyde between the maximum and minimum ventilation rates (4.86 and 28.7 µg m^{-3}) is approximately 23.8 µg m^{-3}. In other words, an 83% reduction in VR (0.24 to 0.04 cfm ft^{-2}) leads to a 490% increase (to 590% of baseline value) in the steady-state indoor concentration of formaldehyde. (These modeled indoor concentrations at the three VR levels assume no indoor reactions. We consider the reaction-based formation of formaldehyde in Scenario C.)

Table 12. Model results from Scenario A: predicted steady-state indoor concentrations of 34 VOCs at three ventilation rates in a Big Box Retail Store: VR_{min} (0.04 cfm ft^{-2}), VR_{max} (0.24 cfm ft^{-2}), and VR_{mid} (0.14 cfm ft^{-2})

Compound	Scenario A-1 VR_{min} Steady State (µg m^{-3})	Scenario A-2 VR_{max} Steady State (µg m^{-3})	Scenario A-3 VR_{mid} Steady State (µg m^{-3})	Concentration Ratio VRmin / VRmax Steady State
Acetaldehyde	16.1	2.73	4.67	5.9
Benzene	3.93	0.66	1.14	6.0
2-Butanone	6.77	1.15	1.96	5.9
2-Butoxyethanol	88.1	14.9	25.6	5.9
Chlorobenzene	0.06	0.01	0.02	6.0
Chloroform	0.95	0.16	0.27	5.9
1,4-DCB	8.12	1.37	2.36	5.9
Dichloromethane	5.14	0.87	1.49	5.9
Ethylbenzene	8.80	1.49	2.55	5.9
Formaldehyde	28.7	4.86	8.33	5.9
n-Hexane	1.22	0.21	0.35	5.8
Naphthalene	1.35	0.23	0.39	5.9
Phenol	5.55	0.94	1.61	5.9
2-Propanol	10.96	1.86	3.18	5.9
2-Propanone	25.0	4.24	7.27	5.9
Styrene	6.77	1.15	1.96	5.9
Tetrachloroethene	3.11	0.53	0.90	
Toluene	116.8	19.8	33.9	5.9
1,1,1-Trichloroethane	1.89	0.32	0.55	5.9
Trichloroethene	3.11	0.53	0.90	5.9
m/p-Xylene	20.71	3.51	6.01	5.9
o-xylene	6.77	1.15	1.96	5.9
TMPD-DIB	1.43	0.24	0.42	6.0
TMPD-MIB	0.37	0.06	0.11	6.2
a-pinene	3.29	0.56	0.95	5.9
a-t pineol	0.24	0.04	0.07	6.0
benzaldehyde	15.2	2.57	4.40	5.9
D5 siloxane	32.6	5.52	9.47	5.9
decanal	15.5	2.63	4.51	5.9
diethylphthalate	0.46	0.08	0.13	5.8
d-limonene	10.83	1.83	3.14	5.9
hexanal	12.72	2.15	3.69	5.9
nonanal	8.04	1.36	2.33	5.9
octanal	2.23	0.38	0.65	5.9
VR ratio: vs. VRmin[a]	---	6.0	3.5	
Mean COC ratio: vs. VRmin[b]	---	0.17	0.29	Mean=5.9

Abbreviations: 1,4-DCB = 1,4-Dichlorobenzene; TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol di-isobutyrate; TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol mono-isobutyrate; D5 siloxane = decamethylcyclopentasiloxane [a] ratio of VR-mid/VR-min or VR-max/VR-min

[b] mean of values for each VOC, for Steady State concentration, of ratio VRmid/VRmin or VRmax/VRmin

Scenario B – Differing day-time and night-time ventilation rates

Both B sub-scenarios (see Table 1 for description) used maximum ventilation at night, but in the daytime, B-1 used minimum ventilation whereas B-2 used mid-level ventilation. Detailed plots for each VOC over time, for the two VR scenarios, are shown in Appendices 2.1 and 2.2, respectively. Four types of plots are included – real-time concentrations, 8-hour moving averages, 24-hour moving averages, and cumulative exposures for specific 8-hour "work shifts" as well as for 24-hour periods.

Figure 8 below shows, as an example, the predicted concentration profile over time for formaldehyde in the two B sub-scenarios, superimposed on the profile for Scenario A with steady VR levels. In Scenario B2, combining VRmid and VRmax, the steady state concentration of formaldehyde at VRmid remains always below the OEHHA chronic REL. After transition from VRmid to VRmax, approximately 3 hours is required for formaldehyde concentrations to diminish to the VRmax steady state level. In Scenario B1, in contrast, the indoor concentration of formaldehyde rises quickly above the REL and approaches the high steady state concentration at VRmin, most of the time greatly exceeding the REL; after transition from VRmin to VRmax, despite starting concentrations below VRmin steady state levels, approximately 2 hours are required for concentrations to diminish to the REL and over 5 hours to diminish to the VRmax steady state. In Scenario B-1, formaldehyde concentrations exceed the 9 $\mu g/m^3$ OEHHA REL for approximately 17 of each 24 hours.

Table 13 provides the modeled concentrations of COCs in indoor air for each of the two ventilation sub-scenarios. For each scenario and compound, the table provides two concentrations: ventilation rate-specific, and overall 24-hour average (24HA) after reaching steady state concentrations. For all VOCs, concentrations in each ventilation rate period and also the 24HA were lower in sub-scenario B2 than B1 (mid-level vs. minimum-level VR during the daytime). The ratios of indoor concentrations for B2/B1 for the studied compounds (Table 13) ranged from 0.39 to 0.50, with a mean of 0.41. Thus, by increasing VRs for 17 hrs/day from VRmin to VRmid (0.04 to 0.14 cfm/ft^{-2} = 3.5 times as high), average indoor 24-hour COC concentrations dropped by about 60%.

Table 14 shows predicted average indoor VOC exposures in a Big Box retail store for different daily occupancy periods, for the two ventilation scenarios: a sequence of three eight-hour shifts starting at 5 AM; a single eight-hour shift starting at 9 AM, and a 24-hour period. For both sub-scenarios, of the three sequential shifts, the lowest average exposures occur during the night shift, almost entirely at VRmax. The various other 8-hour shifts are higher, depending on the proportion of time at a lower VR, with the highest average exposures occurring during the 1 PM-9 PM shift, entirely within the tail end of the lower VR period. For formaldehyde, for example, 1 PM-9 PM occurs entirely at the VRmid steady state in sub-scenario B2, and close to the higher VRmin steady state in sub-scenario B1.

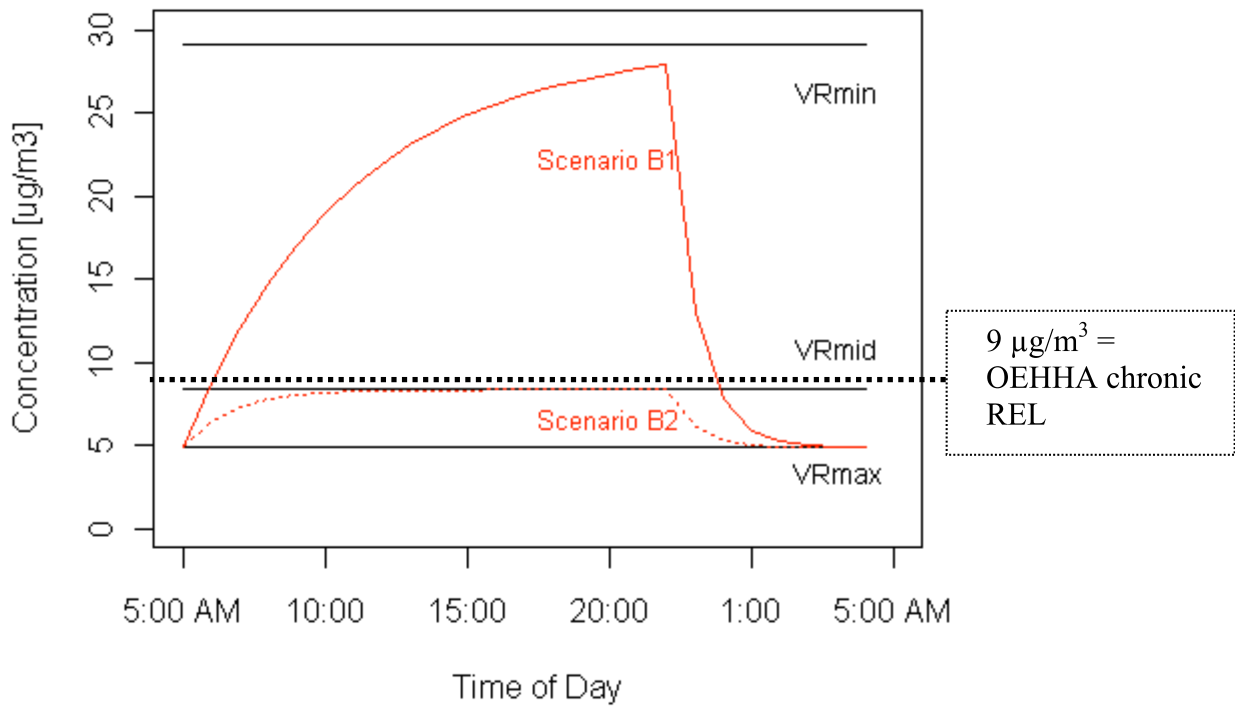


Figure 8. Indoor concentrations predicted for formaldehyde in Scenario B, superimposed on values predicted for VRmin, VRmid, and VRmax in Scenario A. .

Table 13. Model results from Scenarios B1 and B2: predicted average indoor VOC concentrations in a Big Box retail store, for two scenarios with different VRs during two periods. VR_{min} = 0.04 cfm ft^{-2}, VR_{mid} = 0.14 cfm ft^{-2}, and VR_{max} = 0.24 cfm ft^{-2}.

	Scenario B1			Scenario B2			Ratio, 24-hr avg B2/B1
Compound	VR_{max} 10 pm-5 am (µg m^{-3})	VR_{min}: 5 am-10 pm (µg m^{-3})	24h Average (µg m^{-3})	VR_{max} 10 pm-5 am (µg m^{-3})	VR_{mid} 5 am-10 pm (µg m^{-3})	24h Average (µg m^{-3})	
Acetaldehyde	5.48	11.6	9.77	3.14	4.42	4.04	0.41
Benzene	1.33	2.82	2.38	0.77	1.08	0.98	0.41
2-Butanone	2.30	4.87	4.10	1.32	1.86	1.70	0.41
2-Butoxyethanol	30.0	63.4	53.4	17.2	24.2	22.1	0.41
Chlorobenzene	0.02	0.05	0.04	0.01	0.02	0.02	0.50
Chloroform	0.32	0.68	0.57	0.18	0.26	0.24	0.42
1,4-DCB	2.76	5.84	4.93	1.58	2.23	2.04	0.41
Dichloromethane	1.75	3.70	3.12	1.00	1.41	1.29	0.41
Ethylbenzene	2.99	6.33	5.34	1.72	2.42	2.21	0.41
Formaldehyde	9.76	20.6	17.4	5.60	7.88	7.20	0.41
n-Hexane	0.41	0.87	0.74	0.24	0.33	0.30	0.41
Naphthalene	0.46	0.97	0.82	0.26	0.37	0.34	0.41
Phenol	1.89	3.99	3.37	1.08	1.52	1.39	0.41
2-Propanol	3.73	7.89	6.65	2.14	3.01	2.75	0.41
2-Propanone	8.52	18.0	15.2	4.88	6.88	6.28	0.41
Styrene	2.30	4.87	4.10	1.32	1.86	1.70	0.41
Tetrachloroethene	1.06	2.24	1.89	0.61	0.85	0.78	0.41
Toluene	39.7	84.0	70.8	22.8	32.1	29.3	0.41
1,1,1-Trichloroethane	0.64	1.36	1.15	0.37	0.52	0.48	0.41
Trichloroethene	0.29	0.61	0.52	0.17	0.23	0.21	0.41
m/p-Xylene	7.04	14.9	12.6	4.04	5.69	5.20	0.41
o-xylene	2.30	4.87	4.10	1.32	1.86	1.70	0.41
TMPD-DIB	0.49	1.03	0.87	0.28	0.39	0.36	0.41
TMPD-MIB	0.13	0.27	0.22	0.07	0.10	0.09	0.41
a-pinene	1.12	2.36	1.99	0.64	0.90	0.82	0.41
a-terpineol	0.08	0.17	0.14	0.05	0.07	0.06	0.43
benzaldehyde	5.16	10.9	9.19	2.96	4.16	3.80	0.41
D5 siloxane	11.1	23.5	19.8	6.36	8.96	8.19	0.41
decanal	5.28	11.2	9.42	3.03	4.26	3.90	0.41
diethylphthalate	0.16	0.33	0.28	0.09	0.13	0.12	0.39
d-limonene	3.68	7.79	6.57	2.11	2.97	2.72	0.41
hexanal	4.33	9.15	7.72	2.48	3.49	3.19	0.41
nonanal	2.73	5.78	4.88	1.57	2.21	2.02	0.41
octanal	0.76	1.60	1.35	0.43	0.61	0.56	0.41
						mean	0.41

Abbreviations: 1,4-DCB = 1,4-Dichlorobenzene; TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol di-isobutyrate; TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol mono-isobutyrate; D5 siloxane = decamethylcyclopentasiloxan

Table 14. Occupant exposure model results for 34 chemicals from Scenarios B1 and B2. Predicted cumulative indoor VOC exposures for different occupancy periods, using two ventilation sequences in a Big Box retail store. VR_{min} = 0.04 cfm ft^{-2}, VR_{mid} = 0.14 cfm ft^{-2}, and VR_{max} = 0.24 cfm ft^{-2}.

	Cumulative Exposures over Shifts (µg h m^{-3})					Cumulative Exposures over Shifts (µg h m^{-3})				
	Scenario B1 (VR_{min}: 5 am-10 pm; VR_{max}: 10 pm-5 am)					Scenario B2 (VR_{mid}: 5 am-10 pm; VR_{max}: 10 pm-5 am)				
Compound	24h	9am-5pm	5am-1pm	1pm-9pm	9pm-5am	24h	9am-5pm	5am-1pm	1pm-9pm	9pm-5am
Acetaldehyde	236	99.3	67.2	131	54.4	97.3	37.6	33.7	42.6	26.8
Benzene	57.5	24.2	16.4	31.9	13.3	23.7	9.2	8.2	10.4	6.5
2-Butanone	99.1	41.7	28.2	55.0	22.9	40.9	15.8	14.2	17.9	11.2
2-Butoxyethanol	1290	543	368	716	298	532	206	184	233	146
Chlorobenzene	0.9	0.4	0.3	0.5	0.2	0.4	0.1	0.1	0.2	0.1
Chloroform	13.9	5.8	4.0	7.7	3.2	5.7	2.2	2.0	2.5	1.6
1,4-DCB	119	50.1	33.9	66.0	27.4	49.0	18.9	17.0	21.5	13.5
Dichloromethane	75.3	31.7	21.5	41.8	17.4	31.1	12.0	10.8	13.6	8.5
Ethylbenzene	129	54.2	36.7	71.5	29.7	53.1	20.5	18.4	23.3	14.6
Formaldehyde	420	177	120	233	96.9	173	66.9	60.0	75.9	47.7
n-Hexane	17.8	7.5	5.1	9.9	4.1	7.3	2.8	2.5	3.2	2.0
Naphthalene	19.8	8.3	5.6	11.0	4.6	8.2	3.2	2.8	3.6	2.2
Phenol	81.3	34.2	23.1	45.1	18.7	33.5	12.9	11.6	14.7	9.2
2-Propanol	161	67.6	45.7	89.1	37.0	66.2	25.6	22.9	29.0	18.2
2-Propanone	367	154	104	203	84.6	151	58.4	52.4	66.2	41.6
Styrene	99.1	41.7	28.2	55.0	22.9	40.9	15.8	14.2	17.9	11.2
Tetrachloroethene	45.6	19.2	13.0	25.3	10.5	18.8	7.3	6.5	8.2	5.2
Toluene	1710	720	487	949	395	705	272	244	309	194
1,1,1-Trichloroethane	27.7	11.7	7.9	15.4	6.4	11.4	4.4	4.0	5.0	3.1
Trichloroethene	12.5	5.3	3.6	6.9	2.9	5.1	2.0	1.8	2.3	1.4
m/p-Xylene	303	128	86.4	168	69.9	125	48.3	43.3	54.8	34.4
o-xylene	99.1	41.7	28.2	55.0	22.9	40.9	15.8	14.2	17.9	11.2
TMPD-DIB	21.0	8.8	6.0	11.6	4.8	8.7	3.3	3.0	3.8	2.4
TMPD-MIB	5.4	2.3	1.5	3.0	1.2	2.2	0.9	0.8	1.0	0.6
a-pinene	48.1	20.3	13.7	26.7	11.1	19.8	7.7	6.9	8.7	5.5
a-terpineol	3.5	1.5	1.0	1.9	0.8	1.4	0.6	0.5	0.6	0.4
benzaldehyde	222	93.5	63.2	123.2	51.2	91.5	35.4	31.7	40.1	25.2
D5 siloxane	478	201	136	265	110	197	76.1	68.2	86.2	54.2
decanal	227	95.7	64.8	126.2	52.4	93.8	36.2	32.5	41.1	25.8
diethylphthalate	6.8	2.8	1.9	3.7	1.6	2.8	1.1	1.0	1.2	0.8
d-limonene	159	66.8	45.2	88.0	36.6	65.4	25.3	22.7	28.6	18.0
hexanal	186	78.4	53.1	103	43.0	76.8	29.7	26.6	33.6	21.1
nonanal	118	49.6	33.5	65.3	27.2	48.5	18.8	16.8	21.3	13.4
octanal	32.6	13.7	9.3	18.1	7.5	13.5	5.2	4.7	5.9	3.7

Abbreviations: 1,4-DCB = 1,4-Dichlorobenzene; TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol di-isobutyrate; TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol mono-isobutyrate; D5 siloxane = decamethylcyclopentasiloxane

Scenarios A and B differ only in their time patterns of VR. The following text describes contaminant concentrations estimated for these two scenarios in terms of threshold levels of effect. Table 15 shows, for single COCs in different ventilation scenarios, calculated ratios of estimated indoor concentrations divided by available threshold values for chronic non-cancer health effects, odor, and irritancy. Threshold values were available for chronic non-cancer health effects for 21 of 34 COCs, for olfactory effects for 14, and for irritant effects for only three. A number of compounds exceeded 10% of their chronic non-cancer RELS in one or more scenarios – the aldehydes acetaldehyde and formaldehyde, and the aromatics naphthalene and toluene. Formaldehyde had higher concentrations relative to its REL than any other compound, and exceeded the REL for scenarios A1, B1, and D1 with ratios of 3.19, 1.92, and 1.96.

Table 15 also shows that most COCs are far below any known olfactory threshold, although threshold estimates were identified for fewer than half of the listed COCs. Exceptions include three aldehydes – hexanal, nonanal, and octanal – which are above 10% of their olfactory thresholds for most of the scenarios included in the table. Octanal in Scenario A1 exceeded its olfactory threshold. Irritancy threshold data were available for only three COCs. Two of them, 1,4-DCB and diethylphthalate, were in all scenarios below 10% of their irritancy threshold. Formaldehyde, in contrast, reached a steady state level in Scenario A1 that was 30% of its irritancy threshold.

Because VOCs causing human responses through similar biologic mechanisms might have effects jointly even though each single COC were below its specific reference level, we have, for an example group of structurally similar VOCs (aldehydes), totaled the compound-specific ratios into totals for the group. Table 16 provides, for ventilation scenarios A and B, and for thresholds of chronic health effects, odor, and irritancy, the totaled ratios for aldehydes of individual concentrations divided by individual available threshold values. For chronic RELS, the ratio totals for aldehydes exceeded 1.0 for Scenarios A1 and B1; individual ratios for formaldehyde already exceeded 1.0, and dominate the totals. It is evident that were more threshold data available, the ratio totals for Scenarios A3 and B2, now 0.96 and 0.82, might exceed 1.0 as well. For olfactory thresholds, the ratio totals for aldehydes exceeded 1.0 for Scenarios A1 and B1. For olfactory effects, the largest individual COC ratio for B1 was 0.68 for octanal, and thus only the ratio total, but no individual COC ratio, exceeded 1.0; only hexanal, nonanal, and octanal contribute substantially to the total. For Scenarios A3 and B2, the ratio totals were substantially more than the highest individual ratio; i.e., 0.67 vs. 0.33, and 0.57 vs. 0.28, respectively.

Nine COCs had OEHHA cancer UREs available (other COCs may be non-carcinogenic or simply may have not been studied for this). Table 17 allows comparison of equilibrium concentrations in Scenarios A and B to concentrations of the nine COCs corresponding to specific estimated excess levels of risk for cancer. We will not recommend a specific level of excess cancer risk as an appropriate threshold, as this is a complex risk management decision. We note, however, that a 1×10^{-6} cancer risk is associated with a working life occupational exposure to a formaldehyde concentration of 1.1 $\mu g/m^3$, about one-third of the usual *outside* concentration. For the sake of discussion, and following the example of Logue et al. (2010), we will compare various estimated indoor concentrations to concentrations associated with excess cancer risks of 1×10^{-5}. In scenarios A2 and A3, at constant VRmax and VRmid respectively, and in scenario B2 using both VR max and VRmid, none of the nine COCs exceeded a concentration associated with excess cancer risks of 1 x 10^{-5}. In scenario A1, at constant VRmin, however, three COCs exceeded this level: benzene, 1,4-DCB, and formaldehyde, with concentration to threshold ratios of 1.5, 1.4, and 2.6 respectively. Also, in scenario B2, using both VRmax and VRmin, formaldehyde exceeded this level, with a concentration to threshold ratio of 1.6.

Table 15. Comparison of selected model results from Scenarios A, B, and D with available OEHHA RELs, olfactory thresholds, and irritancy thresholds[1]: threshold analysis of 34 single COCs, using limited available threshold data

	(µg m-3)	(µg m-3)	(µg m-3)	A1	A2	A3	A1	A2	A3	B1	B2	B1	B2
Compound	OEHHA Chronic REL	Olfactory Threshold	Irritancy Threshold	Ratio of SS Concentration to REL			Ratio of SS Concentration to Olfactory Threshold			Ratio of 24 hr Average to REL		Ratio of 24 hr Average to Olfactory Threshold	
Acetaldehyde	140	343		0.12	0.02	0.03	0.05	0.01	0.01	0.07	0.03	0.03	0.01
Benzene	60			0.07	0.01	0.02				0.04	0.02		
2-Butanone													
2-Butoxyethanol	960	1,643		0.09	0.02	0.03	0.05	0.01	0.02	0.06	0.02	0.03	0.01
Chlorobenzene	1,000			0.00	0.00	0.00				0.00	0.00		
Chloroform	300			0.00	0.00	0.00				0.00	0.00		
1,4-DCB	800	289	3,427	0.01	0.00	0.00	0.03	0.00	0.01	0.01	0.00	0.02	0.01
Dichloromethane	400			0.01	0.00	0.00				0.01	0.00		
Ethylbenzene	2,000			0.00	0.00	0.00				0.00	0.00		
Formaldehyde	9	1,067	95	3.19	0.54	0.93	0.03	0.00	0.01	1.93	0.80	0.02	0.01
n-Hexane	7,000			0.00	0.00	0.00				0.00	0.00		
Naphthalene	9	79		0.15	0.03	0.04	0.02	0.00	0.00	0.09	0.04	0.01	0.00
Phenol	200	423		0.03	0.00	0.01	0.01	0.00	0.00	0.02	0.01	0.01	0.00
2-Propanol	7,000			0.00	0.00	0.00				0.00	0.00		
2-Propanone	31,200			0.00	0.00	0.00				0.00	0.00		
Styrene	900	596		0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Tetrachloroethene	35			0.09	0.02	0.03				0.05	0.02		
Toluene	300			0.39	0.07	0.11				0.24	0.10		
1,1,1-Trichloroethane	1,000			0.00	0.00	0.00				0.00	0.00		
Trichloroethene	600			0.01	0.00	0.00				0.00	0.00		
m/p-Xylene	700	1,390		0.03	0.01	0.01	0.01	0.00	0.00	0.02	0.01	0.01	0.00
o-xylene	700	3,690		0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
TMPD-DIB													
TMPD-MIB													
a-pinene													
a-t pineol													

Table 15 (continued). Comparison of selected model results from Scenarios A, B, and D with available OEHHA RELs, olfactory thresholds, and irritancy thresholds[1]: threshold analysis of 35 single COCs, using limited available threshold data

	(µg m-3)	(µg m-3)	(µg m-3)	A1	A2	A3	A1	A2	A3	B1	B2	B1	B2
Compound	OEHHA Chronic REL	Olfactory Threshold	Irritancy Threshold	Ratio of SS Concentration to REL			Ratio of SS Concentration to Olfactory Threshold			Ratio of 24 hr Average to REL		Ratio of 24 hr Average to Olfactory Threshold	
benzaldehyde		182					0.08	0.01	0.02			0.05	0.02
D5 siloxane													
decanal													
diethylphthalate			500										
d-limonene		4,402					0.00	0.00	0.00			0.00	0.00
hexanal		32					0.40	0.07	0.12			0.24	0.10
nonanal		13					0.62	0.10	0.18			0.38	0.16
octanal		2					1.12	0.19	0.33			0.68	0.28

Abbreviations: 1,4-DCB = 1,4-Dichlorobenzene; TMPD-DIB = 2,2,4-trimethyl-1,3-pentanediol di-isobutyrate; TMPD-MIB = 2,2,4-trimethyl-1,3-pentanediol mono-isobutyrate; D5 siloxane = decamethylcyclopentasiloxane

[1] RELs, odor thresholds, and irritancy thresholds in this Table but not in Table 2 were obtained from information sources other than ASHRAE 62.1-2010 Appendix B-3 (personal communication, S. Parthasarathy, from work on the Healthy Zero Energy Building Program)

[2] based on ATSDR chronic MRL of 200 ppb

[3] based on ATSDR chronic MRL of 13,000 ppb

[4] REL of 700 µg m^{-3} applies to all xylenes isomers; thus summed concentrations for all isomers should be compared to this

Table 16. Comparison of selected model results from Scenarios A and B with available OEHHA RELs and olfactory thresholds[1]: threshold analysis of single COCs, using two example structural groupings of COCs and limited available threshold data (values exceeding 1.0 in bold)

Compound	OEHHA Chronic REL (µg m-3)	Olfactory Threshold (µg m-3)	Irritancy Threshold (µg m-3)	Ratio of Steady State Concentration to REL: A1 VR min	A2 VR max	A3 VR mid	Ratio of Steady State Concentration to olfactory threshold: A1 VR min	A2 VR max	A3 VR mid	Ratio of 24 hr average to REL: B1	B2	Ratio of 24 hr average to olfactory threshold: B2	B2
ALDEHYDES													
Acetaldehyde	140	343		0.12	0.02	0.03	0.05	0.01	0.01	0.07	0.03	0.03	0.01
Benzaldehyde		182					0.08	0.01	0.02			0.05	0.02
Decanal													
Formaldehyde	9	1,067	95	**3.19**	0.54	0.93	0.03	0.00	0.01	**1.92**	0.79	0.02	0.01
Hexanal		32					0.40	0.07	0.12			0.24	0.10
Nonanal		13					0.62	0.10	0.18			0.38	0.16
Octanal		2					**1.12**	0.19	0.33			0.68	0.28
ALDEHYDE RATIO TOTALS				**3.30**	0.56	0.96	**2.29**	0.38	0.67	**1.99**	0.82	**1.39**	0.57

Abbreviations; 1,4-DCB = 1,4-Dichlorobenzene

[1] RELs and odor thresholds in this Table but not in Table 2 were obtained from information sources other than ASHRAE 62.1-2010 Appendix B-3 (personal communication, S. Parthasarathy, from work on the Healthy Zero Energy Building Program)

[2] REL of 700 µg m^{-3} applies to all xylenes isomers; thus summed concentrations for all isomers should be compared to this

Table 17. Comparison of selected model results from Scenarios A and B with available OEHHA cancer unit risk estimates: threshold analysis of single COCs (concentrations exceeding excess cancer risks of 1 x 10^{-5} are in bold type)

Compound	Concentration Producing Specified Excess Cancer Risk from Working Life Occupational Exposure (µg/m³)			Scenario: A1 VR min — Steady State Concentrations (µg/m³)	A2 VR max	A3 VR mid	B1 — 24 Hr Average Concentrations (µg/m³)	B2
	10^{-4}	10^{-5}	10^{-6}					
Acetaldehyde	242	24.2	2.4	16.1	2.73	4.67	9.77	4.04
Benzene	26	2.6	0.3	**3.93**	0.66	1.14	2.38	0.98
Chloroform	123	12.3	1.2	0.95	0.16	0.27	0.57	0.24
1,4-DCB	59	5.9	0.6	**8.12**	1.37	2.36	4.93	2.04
Dichloromethane	653	65.3	6.5	5.14	0.87	1.49	3.12	1.29
Ethylbenzene	261	26.1	2.6	8.80	1.49	2.55	5.34	2.21
Formaldehyde	109	10.9	1.1	**28.7**	4.86	8.33	**17.4**	7.20
Naphthalene	19	1.9	0.2	1.35	0.23	0.39	0.82	0.34
Trichloroethene	327	32.7	3.3	3.11	0.53	0.90	0.52	0.21

Scenario C – Considering ambient criteria pollutants

Table 18 provides the indoor decay rates used in the models (Equation 5 in Table 7) for the three criteria pollutants to predict indoor concentrations.

Table 18. Indoor decay rates reported in the literature.

Compound	λ [1/h]	Reference
NO_2	0.7	(Weschler et al. 1994)
CO	0	---
O_3	3.6	(Weschler 2000)

Data on real-time outdoor and predicted indoor concentrations of three criteria pollutants (NO_2, CO, and O_3) for two cities and four seasons, and at each of three constant VRs, are provided as two kinds of plots: in Appendix 3.1, over 15 days, with separate plots for different VR scenarios; and in Appendix 3.2, over 24 hours, with all three scenarios in each plot. Table 19 shows two-week average indoor concentrations, for each city, in each season, for various shifts/periods, for the three fixed VR scenarios. (For each two-week period, the first 48 hours of prediction were omitted to exclude the effect of arbitrary selection of the initial indoor value) Table 20 provides further information on indoor vs. outdoor levels of specific criteria pollutants for different VRs, seasons, and cities. The indoor/outdoor ratios for cumulative exposures, by pollutant, provide insights into the effects of VR on the ability of the building to protect occupants from pollutant exposures, depending on the schedule in the building, the outdoor pattern of variation of the pollutant, and the pollutant's reactivity in the building. Appendix 3.3 shows example variation in indoor concentrations of the three criteria pollutants at three ventilation rates, in two cities, over a 12-day period in 4 seasons.

No outdoor level of these pollutants apparently exceeded any NAAQS standard during the times studied. Appendices 3.1 and 3.2 show that indoor levels track outdoor levels in all cases, but the higher the VR, the shorter the lag for indoor response and the more closely the indoor peaks approach the magnitude of the outdoor peaks. Thus, VR has the opposite effect on indoor concentrations of *outdoor*-generated contaminants as it has on *indoor*-generated contaminants.

Table 20 shows that indoor concentrations of O_3 tended to be lower during the day at all seasons in both cities, but were particularly low with lower VRs. On the other hand, overnight levels indoors in both cities were generally higher than outdoor levels in summer at all VR levels, especially VRmin. Appendix 3.2, Figures 5 and 6, shows that the peak O_3 values for specific shifts seen in Table 17 occurred with VRmax for 1-9 pm in summer, tending to correspond to the highest outdoor daily peaks. For O_3 (Table 19), indoor concentrations approached 50-60% of the 8-hr standard in LA and Sacramento in summer for some shifts, but only for VRmid and VRmax. Lower VRs were substantially protective for occupants against outdoor O_3 during the summer, when the highest ambient levels occurred, especially for VRmin during the daytime, in both LA (estimated indoor concentrations with VRmin were 54% of those with VRmax) and Sacramento (59%). Similar reductions occurred in daytime in both cities in all seasons.

Table 19 shows that NO_2 levels exceeded 50% of the annual standard in LA during some shifts in the spring, at all VR levels, and at night in the summer at mid and max VRs, but were otherwise between 30-50% of this standard in LA and 10-30% in Sacramento. Peak values in LA, in spring, corresponded to the peak outdoor values seen in Appendix 3.2, Figure 3. Lower VRs were only slightly protective for building occupants against outdoor NO_2. For instance, during spring periods when indoor NO_2 concentrations exceeded 50% of the annual standard in LA, the relative indoor levels estimated for VRmin and VRmid in different shifts, relative to VRmax, ranged from 88-99% and 97-101%, respectively. Given this limited protection, the most protective conditions were estimated for VRmin, in spring during the daytime in LA (88-92% of VRmax levels) and during the night in Sacramento (82% of VRmax), and in summer during the night in both LA (86%) and Sacramento (81%). Table 20 shows that for NO_2, VRmin provided some protection in afternoons in winter in LA. Indoor locations at all VRs had increased cumulative exposures overnight in all seasons in LA and in some non-winter seasons in Sacramento.

Appendix 3.1 shows that ambient CO levels were far below NAAQS 8-hour ambient standards – about 9% at the most. The highest indoor peaks evident for specific shifts in Los Angeles in Table 19 tended to correspond to the outdoor peaks seen in Appendix 3.2, Figure 1. Lower VRs offered little indoor protection against outdoor CO levels, with some exceptions such as VRmin during winter nights, in both LA and Sacramento (88% of VRmax levels). Table 20 shows that for CO, over a 24-hour period, the VR makes little difference for indoor exposures in either city. All VRs provide small amounts of protection in each city at specific seasons and times. VRmin provides additional small amounts of protection overnight in fall in LA and overnight in winter in Sacramento. VRmin appears to increase indoor CO exposures during the daytime shift in some seasons.

Table 19. Model results from Scenario C: average over two weeks[1] for indoor concentrations of ambient air pollutants (CO, NO_2, and O_3) at different time periods, for four seasons with three different ventilation rate scenarios, for Sacramento and Los Angeles

Units: µg m^{-3}		Average over two weeks[1], VR_{min}				Average over two weeks[1], VR_{mid}				Average over two weeks[1], VR_{max}				NAAQS[2]
Schedule	Pollutant	Fall	Spr.	Sum.	Win.	Fall	Spr.	Sum.	Win.	Fall	Spr.	Sum.	Win.	
					Los Angeles									
1pm to 9pm	CO	353	835	698	558	316	790	665	537	315	776	657	553	10,000[a]
5am to 1pm	CO	425	871	736	662	435	897	745	612	432	903	744	601	40,000[b]
9am to 5pm	CO	395	877	731	598	355	875	723	528	337	865	717	510	
9pm to 5am	CO	397	818	704	734	437	823	732	791	446	829	742	782	
24 Hours	CO	392	841	713	652	396	837	714	647	398	836	714	646	
1pm to 9pm	NO_2	37.0	50.2	39.2	38.7	39.1	53.9	37.3	45.3	39.7	54.2	36.8	46.3	100[c]
5am to 1pm	NO_2	36.3	45.6	44.5	30.3	38.2	46.6	46.9	31.0	39.1	47.9	47.3	32.2	
9am to 5pm	NO_2	37.0	48.5	43.3	33.4	39.2	53.4	44.0	38.0	39.4	54.6	43.7	39.5	
9pm to 5am	NO_2	39.9	51.2	44.6	37.9	40.8	51.2	50.5	35.9	40.3	50.4	51.6	34.5	
24 Hours	NO_2	37.8	49.0	42.8	35.6	39.4	50.6	44.9	37.4	39.7	50.8	45.3	37.7	
1pm to 9pm	O_3	51.6	47.6	69.6	23.1	70.8	67.5	100	29.8	73.0	71.2	105	30.0	170[a]
5am to 1pm	O_3	22.7	23.6	24.3	12.6	32.7	30.3	35.3	17.3	37.1	33.1	41.1	19.1	260[b]
9am to 5pm	O_3	39.9	34.9	48.4	19.6	63.9	53.3	80.3	30.1	70.8	59.2	89.9	33.2	
9pm to 5am	O_3	27.1	32.1	37.4	12.1	20.5	29.8	26.2	11.2	18.6	28.7	22.0	11.4	
24 Hours	O_3	33.8	34.4	43.8	15.9	41.3	42.5	53.9	19.4	42.8	44.3	56.0	20.1	
					Sacramento									
1pm to 9pm	CO	368	415	336	391	326	382	333	370	332	382	332	373	10,000[a]
5am to 1pm	CO	480	482	334	439	445	490	338	431	435	490	341	432	40,000[b]
9am to 5pm	CO	421	454	339	421	354	416	342	400	335	398	342	392	
9pm to 5am	CO	506	456	338	475	570	474	337	499	571	474	336	494	
24 Hours	CO	451	451	336	435	448	449	336	433	446	449	336	433	
1pm to 9pm	NO_2	16.6	15.1	11.9	17.0	14.2	13.8	10.2	17.6	14.7	14.1	9.9	18.3	100[c]
5am to 1pm	NO_2	25.1	21.0	15.6	19.2	24.9	21.0	17.0	19.6	24.5	20.7	17.1	19.9	
9am to 5pm	NO_2	21.0	17.9	14.3	18.0	17.5	15.3	13.4	17.3	16.2	14.4	12.8	16.8	
9pm to 5am	NO_2	25.7	21.2	13.6	21.7	30.8	24.7	15.6	23.3	31.0	25.0	16.1	22.8	
24 Hours	NO_2	22.5	19.1	13.7	19.3	23.3	19.8	14.3	20.2	23.4	20.0	14.4	20.4	
1pm to 9pm	O_3	53.7	51.2	70.0	33.4	77.2	72.3	98.7	43.7	81.2	75.7	104	45.2	170[a]
5am to 1pm	O_3	24.0	24.5	34.6	24.3	30.1	30.8	43.8	29.4	33.2	34.0	48.0	31.0	260[b]
9am to 5pm	O_3	37.4	37.6	51.9	28.7	58.4	58.1	79.3	39.5	65.4	64.7	87.9	42.9	
9pm to 5am	O_3	35.0	35.2	47.3	26.7	31.1	33.0	43.0	30.0	29.6	31.8	41.0	30.9	
24 Hours	O_3	37.5	37.0	50.6	28.1	46.1	45.3	61.8	34.4	47.9	47.1	64.1	35.7	

[1] First 48 hours of each two-week period omitted to exclude effect of arbitrary initial indoor value
[2] National Ambient Air Quality Standard. Averaging times from NAAQS: a = 8 hr; b = 1 hr; c = 1 year

Table 20. Model results from Scenario C: indoor/outdoor ratios of cumulative exposures (concentration x time), for outdoor air criteria pollutants (CO, NO_2, and O_3) for different shifts/time periods in four seasons and two cities, with three different VR scenarios

Pollutant	Period	VR min				VR mid				Vrmax			
		Fall	Sprng	Summ	Wint	Fall	Sprng	Summ	Wint	Fall	Sprng	Summ	Wint
							LOS ANGELES						
CO	1pm to 9pm	1.06	1.12	1.08	0.88	0.95	1.06	1.02	0.85	0.95	1.04	1.01	0.87
	24 Hours	0.98	1.01	1.00	1.02	0.99	1.00	1.00	1.01	0.99	1.00	1.00	1.01
	5am to 1pm	1.01	0.95	0.99	1.15	1.03	0.98	1.01	1.06	1.02	0.99	1.00	1.04
	9am to 5pm	1.28	1.06	1.06	1.31	1.15	1.05	1.05	1.15	1.09	1.04	1.04	1.12
	9pm to 5am	0.90	0.98	0.93	1.03	0.98	0.98	0.97	1.11	1.00	0.99	0.98	1.09
NO_2	1pm to 9pm	0.88	0.93	0.99	0.81	0.93	0.99	0.94	0.95	0.94	1.00	0.93	0.97
	24 Hours	0.94	0.96	0.93	0.93	0.98	0.99	0.98	0.98	0.98	0.99	0.99	0.99
	5am to 1pm	0.90	0.87	0.95	0.85	0.94	0.89	1.00	0.86	0.96	0.92	1.01	0.90
	9am to 5pm	0.96	0.87	1.07	0.74	1.02	0.96	1.08	0.85	1.02	0.98	1.08	0.88
	9pm to 5am	1.05	1.09	0.87	1.22	1.07	1.09	0.99	1.16	1.05	1.07	1.01	1.11
O_3	1pm to 9pm	0.77	0.66	0.69	0.91	1.05	0.94	1.00	1.18	1.08	0.99	1.04	1.19
	24 Hours	0.75	0.73	0.74	0.75	0.91	0.90	0.91	0.91	0.95	0.94	0.94	0.95
	5am to 1pm	0.44	0.56	0.39	0.49	0.63	0.72	0.56	0.67	0.71	0.78	0.66	0.74
	9am to 5pm	0.48	0.48	0.44	0.51	0.78	0.73	0.73	0.78	0.86	0.82	0.82	0.86
	9pm to 5am	1.62	1.18	2.51	0.93	1.23	1.09	1.76	0.86	1.12	1.05	1.48	0.88
							SACRAMENTO						
CO	1pm to 9pm	0.94	1.03	1.00	0.91	0.84	0.94	1.00	0.86	0.85	0.94	0.99	0.87
	24 Hours	1.02	1.01	1.00	1.00	1.01	1.00	1.00	1.00	1.01	1.00	1.00	1.00
	5am to 1pm	1.16	1.00	0.96	1.03	1.08	1.02	0.97	1.01	1.05	1.02	0.98	1.02
	9am to 5pm	1.43	1.23	1.01	1.20	1.20	1.13	1.02	1.14	1.14	1.08	1.02	1.12
	9pm to 5am	0.96	1.01	1.03	1.06	1.08	1.04	1.03	1.12	1.08	1.04	1.03	1.11
NO_2	1pm to 9pm	0.86	0.87	1.10	0.77	0.73	0.80	0.95	0.80	0.76	0.82	0.92	0.84
	24 Hours	0.96	0.95	0.95	0.94	0.99	0.98	0.98	0.98	1.00	0.99	0.99	0.99
	5am to 1pm	1.11	1.09	0.95	0.97	1.10	1.09	1.04	1.00	1.08	1.08	1.04	1.01
	9am to 5pm	1.69	1.46	1.25	1.20	1.40	1.25	1.17	1.16	1.30	1.17	1.12	1.13
	9pm to 5am	0.91	0.89	0.83	1.08	1.09	1.03	0.96	1.16	1.10	1.05	0.99	1.14
O_3	1pm to 9pm	0.68	0.69	0.69	0.76	0.98	0.97	0.97	0.99	1.03	1.02	1.02	1.02
	24 Hours	0.74	0.74	0.75	0.75	0.91	0.91	0.91	0.91	0.94	0.94	0.95	0.95

5am to 1pm	0.53	0.53	0.54	0.67	0.67	0.67	0.68	0.81	0.74	0.74	0.75	0.86
9am to 5pm	0.45	0.47	0.49	0.57	0.71	0.73	0.75	0.79	0.79	0.82	0.83	0.85
9pm to 5am	1.21	1.18	1.24	0.82	1.08	1.12	1.13	0.91	1.02	1.07	1.07	0.94

Scenario D – Considering ozone + d-limonene reaction

Both sub-scenarios D1 and D2, which consider formaldehyde produced by indoor chemical reactions, have VRmax for seven hours at night. For 17 hours in the daytime, D1 has VRmin and D2 has VRmid. For detailed plots of predicted indoor formaldehyde concentrations resulting from indoor sources plus production from d-limonene-ozone reactions, in two cities, in four seasons, and for VR scenarios D1 and D2, see Appendix 4.1 for estimates over four days. For cumulative exposures over 15 days for D1 and D2 respectively, see Appendices 4.2 and 4.3. These plots reflect periods after initial steady-state concentrations of formaldehyde were reached.

Table 21 summarizes the predicted increase in indoor formaldehyde concentration resulting from ozone/d-limonene reactions, in two cities, over four seasons, and with the two VR scenarios. The formaldehyde concentrations for D1 and D2 differ from those for B1 and B2 (Table 13) only by the production of additional formaldehyde from ozone/d-limonene reactions. Twenty-four-hour average indoor formaldehyde concentrations were, for scenarios D1 and D2, 17.3 and 7.14 $\mu g\ m^{-3}$, respectively. From Table 21, predicted increases due to indoor reactions varied across the seasons, with lowest values in winter and highest values in summer. For Scenarios D1 and D2 respectively, the maximum increases in LA were 0.24 and 0.11$\mu g\ m^{-3}$ and in Sacramento, 0.27 and 0.13 For scenario D1, baseline levels of 17.3 $\mu g\ m^{-3}$ would be increased by 0.6-1.6%, and for scenario D2, baseline levels of 7.14 $\mu g\ m^{-3}$ would be increased by 0.6-1.8%, depending on location and season. These small increases would not substantially change exposures or risks.

Table 21. Scenario D: ozone/d-limonene reaction-related production of formaldehyde during four seasons in Los Angeles CA and Sacramento CA under two ventilation scenarios.

$\mu g\ m^{-3}$ City	Indoor formaldehyde concentration increase Fall	Spr.	Sum.	Win.	Baseline formaldehyde concentration (24-h average)	Range of proportional increases over baseline
Ventilation Scenario D1 (VRmin: 5 am-10 pm; VRmax: 10 pm-5 am)						
LA	0.20	0.20	0.24	0.10	**17.3**	0.6-1.4%
Sac	0.22	0.20	0.27	0.15	**17.3**	0.9-1.6%
Ventilation Scenario D2 (VRmid: 5 am-10 pm; VRmax: 10 pm-5 am)						
LA	0.09	0.09	0.11	0.04	7.14	0.6-1.5%
Sac	0.10	0.09	0.13	0.07	7.14	1.0-1.8%

Scenario E – Air cleaning

Typical air cleaners can be installed either in the HVAC system (the typical configuration) or as a stand-alone unit. For these analyses, we are only concerned about indoor concentration as a function of effective removal efficiency. Therefore the effective flow through the cleaning unit is the amount of indoor air passing through the cleaner. A typical HVAC unit air cleaner would clean both incoming fresh air and returning indoor air.

See Appendix 5.1 for a table of steady-state concentrations of 34 chemicals at three constant VR levels, for Zeta (pass-through) values ranging from 0 to1. See Appendix 5.2 for plots of steady state concentrations of COCs, as zeta varies from 0 to 1, at three different constant VRs, with shading for the range of removal feasible with available technology. Even pass-through as high as 80% (removal efficiencies as low as 20%) still produces a large reduction in indoor steady state COC concentrations, especially at low VRs. For instance (see Table 22), steady state indoor concentrations would be 5.9 times as high at VRmin as at VRmax, but a filter with 80% pass-through (20% removal efficiency) substantially reduces this to 2.0 times.

Table 22. Steady-state indoor concentrations of formaldehyde, at three different constant VRs, with air-cleaning of different efficiencies/pass-through

Zeta	Removal Efficiency	VR mode			relative increase in formaldehyde concentration, VR min vs. VR max
		max	mid	min	
1.0	0	4.86	8.33	**28.69**	5.9
0.8	0.2	2.97	3.98	6.04	2.0
0.6	0.4	2.14	2.61	3.37	1.6
0.4	0.6	1.67	1.95	2.34	1.4
0.2	0.8	1.37	1.55	1.79	1.3
0	1.0	1.16	1.29	1.45	1.3

Scenario F - Application of local ventilation strategies with air curtain between two zones

The space is divided into zone 1, the smaller zone with higher contaminant emissions, and zone 2, the larger room. An air curtain limits airflow from zone 1 to zone 2. Table 23 shows that, for a wide range of ACH between the two zones (i.e., flow between the zones divided by the volume of the small zone), the greater the proportion of exhaust air from the large zone redirected into the smaller zone with higher emissions, the more both the average and steady state concentrations of formaldehyde in both zones decrease (see also the table in Appendix 6.1).

Creating an effective air barrier in a large open space such as a big box store may be challenging, and may require a combination of an air barrier and a physical partition. In this analysis, we considered a range of flows passing through an air curtain, between the spaces. High flow would reflect a less effective air curtain, and low flow a very effective air curtain.

Figure 9 provides example plots taken from Appendix 6.2, showing that, for fixed levels of F02 (i.e., air flow from outside to zone 2), as F12 and F21 increase, the equilibrium concentrations of formaldehyde in both spaces decrease. Figures 10 and 11 show that the greater the proportion of air exhausted from the large into the smaller zone, the lower the concentrations in zone 1, and with no adverse effect on concentrations in zone 2. The combinations of VRmid with almost all of

Table 23. Model results for Scenario F: retail space ventilation rate 0.6 h^{-1}. Retail space divided into two spaces separated by an air curtain, with higher formaldehyde (HCHO)-emitting products in the smaller space (zone 1).

		SS Concentration Formaldehyde	
Inter-zone (F12) ACH[1] h^{-1}	Large zone exhaust redirect[2] %	Zone 1 (small zone) $\mu g\ m^{-3}$	Zone 2 (large zone) $\mu g\ m^{-3}$
0.01	0	**25.3**	2.69
0.01	10	**20.1**	2.66
0.01	25	**15.6**	2.63
0.01	50	**11.8**	2.61
0.01	75	**9.65**	2.60
0.01	90	8.79	2.60
0.1	0	**22.5**	3.60
0.1	10	**18.6**	3.40
0.1	25	**14.9**	3.21
0.1	50	**11.5**	3.03
0.1	75	**9.57**	2.93
0.1	90	8.77	2.89
1	0	**13.7**	6.53
1	10	**12.8**	6.19
1	25	**11.6**	5.77
1	50	**10.2**	5.26
1	75	**9.12**	4.89
1	90	8.62	4.71
2	0	**11.5**	7.26
2	10	**11.1**	7.01
2	25	**10.4**	6.69
2	50	**9.58**	6.24
2	75	8.89	5.88
2	90	8.54	5.69
5	0	**9.77**	7.85
5	10	**9.59**	7.72
5	25	**9.35**	7.54
5	50	8.97	7.26
5	75	8.63	7.01
5	90	8.45	6.88
10	0	**9.08**	8.08
10	10	**9.00**	8.01
10	25	8.87	7.90
10	50	8.68	7.74
10	75	8.50	7.59
10	90	8.40	7.50

[1]Flow from small to large zone/volume of small zone (F12/V2, h^{-1})
[2]Percent of total air flow exiting large zone that exits via the small zone

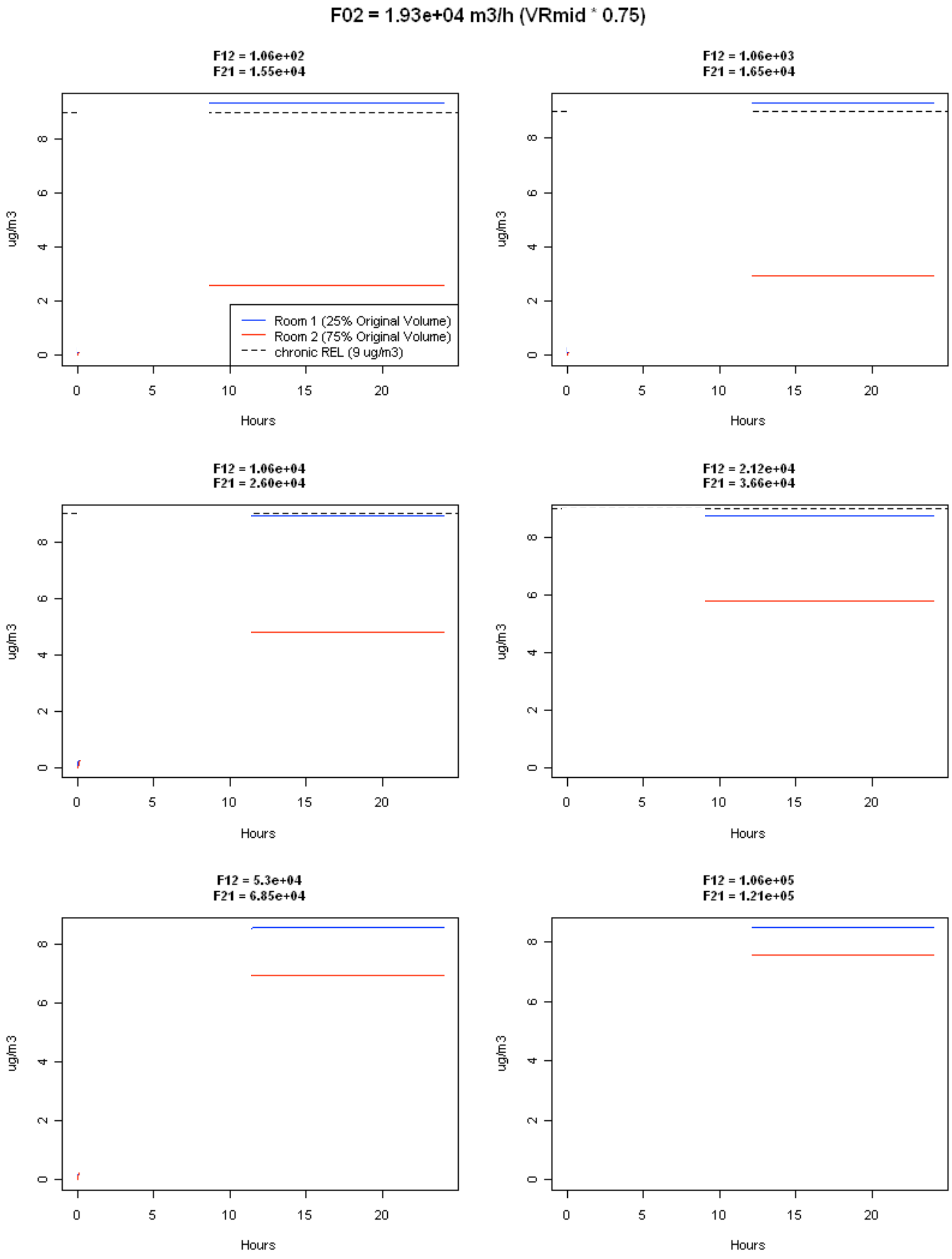


Figure 9. Example plots for Scenario F: indoor formaldehyde concentrations over time in Zone 1 and Zone 2, for specified F02 based on VRmid, and for 6 combinations of values for F12 and F21 (concentrations during initial hours excluded to omit modeling artifact from non-steady state conditions)

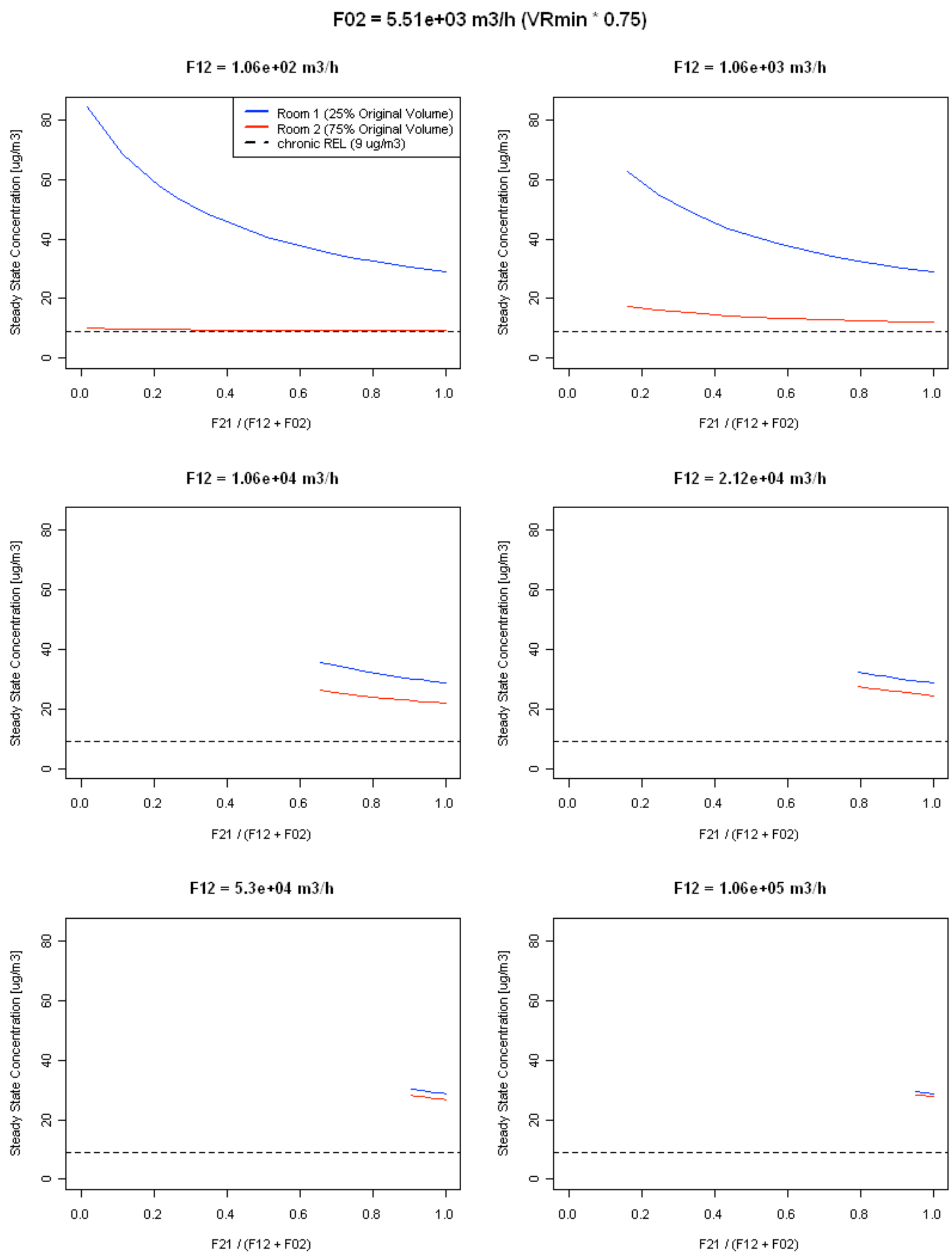
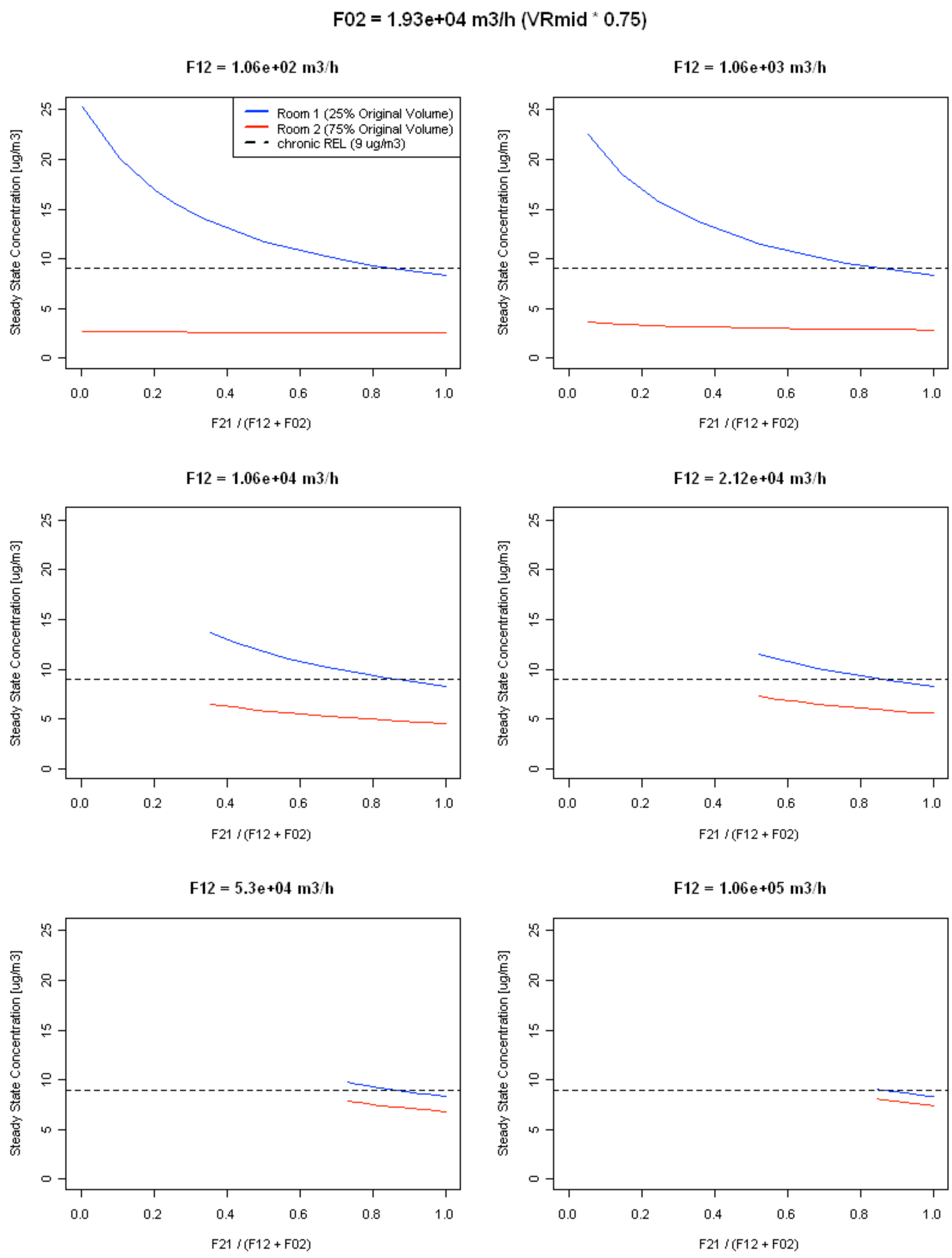


Figure 10. Scenario F – Steady state indoor air concentrations of formaldehyde in Zones 1 and 2, at specified F02 based on VRmin, and six values of F12, as F21 varies



Scenario F – Steady state indoor air concentrations of formaldehyde in Zones 1 and 2, at specified F02 based on VRmid, and six values of F12, as F21 varies

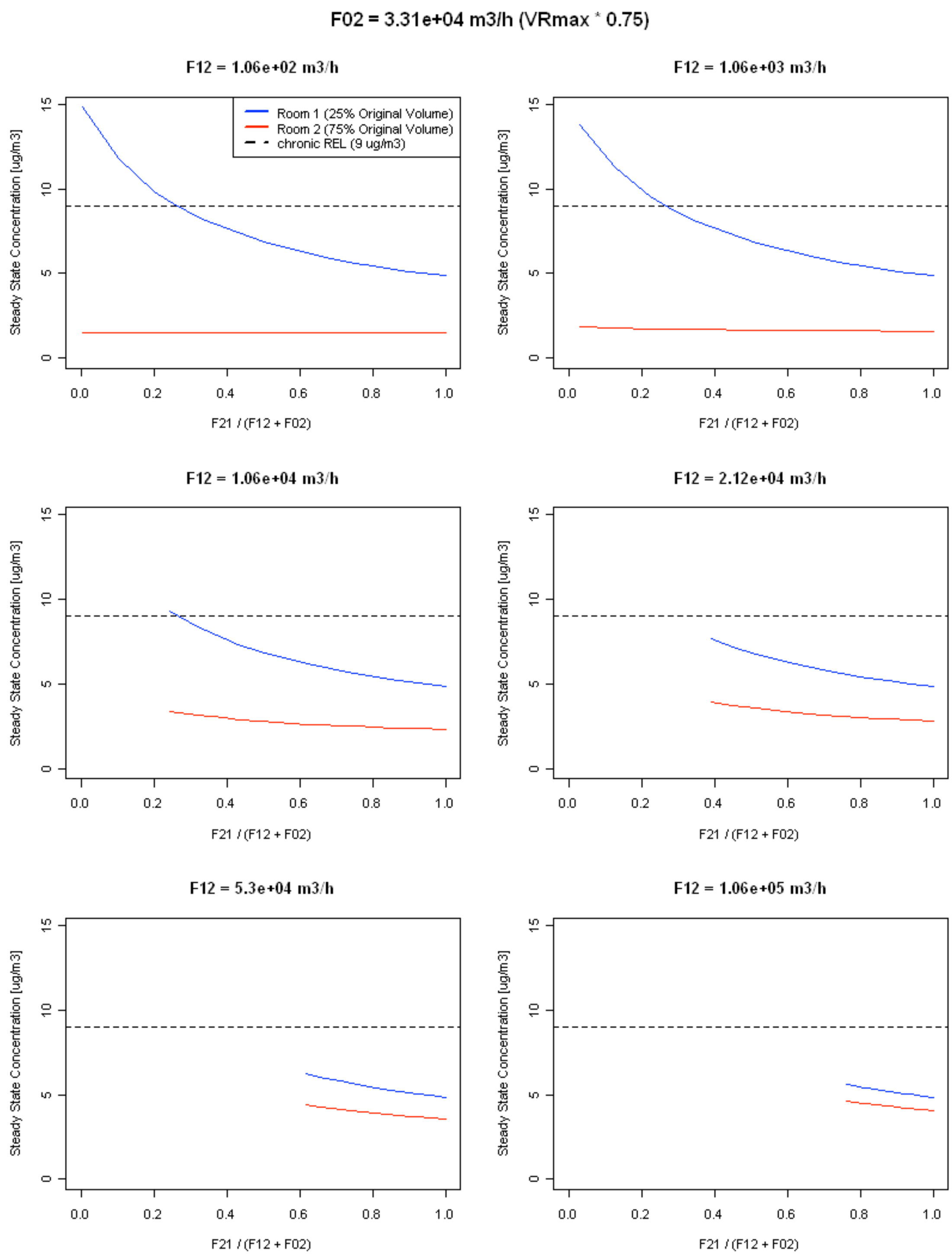


Figure 11. Scenario F – Steady state indoor air concentrations of formaldehyde in Zones 1 and 2, at specified F02 based on VRmax, and six values of F12, as F21 varies.

zone 2 exhaust into zone 1, or VR max with at least half of zone 2 exhaust into zone 1, achieve steady state formaldehyde levels in zone1 below the OEHHA REL.

Results – Energy Modeling

Energy simulation results

Figure 12 gives the stacked total building cooling and heating energy use in three climates over the full range of A and B ventilation scenarios. For each ventilation scenario, results are given for three climates, Oakland, El Centro and Mount Shasta, representing the low energy use, cooling dominated, and heating dominated extremes. The B scenarios are labeled with their day-time/night-time ventilation rates as specified in Table 13.

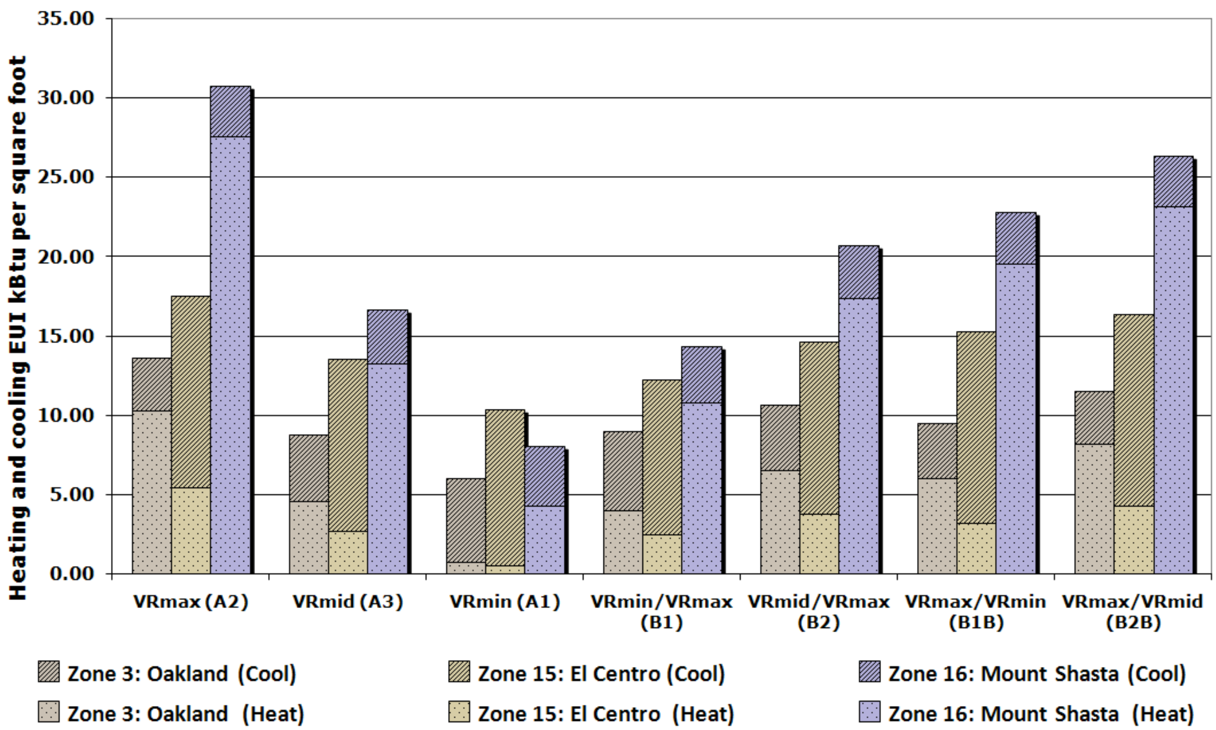


Figure 12. Cooling and heating energy use in three climates over seven ventilation scenarios

For zone 16 (Mount Shasta) the change in ventilation rate, from 1 ACH (VRmax) to 0.17 ACH (VRmin), reduced the gas heating energy use by 85%, from 27.6 kBtu/squ. ft., to 4.4 kBtu/squ. ft. Heating gas energy use falls by 90% in El Centro if ventilation rates are changed from VRmax to VRmin. As shown later heating energy use is a small fraction of total energy use in El Centro and a moderate fraction of total building energy use in El Centro

Comparisons between scenario B1 and B1B indicate a significant heating energy use penalty in the colder climate of Mount Shasta under the B1B scenario. This can be explained by two complementary factors; firstly the duration of day-time operation exceeds night-time operations leading to increased overall air flow for the B1B (VRmax/VRmin) scenario; secondly the night-time operation heating temperature set points are setback to 15.6° C (60° F) resulting reduced night-time heating demand. In moderate climates such as Oakland, some cooling energy savings are seen for the B1B scenario, as increased night-time ventilation provides some additional cooling.

Tables A7-1, A7-2, and A7-3 in Appendix 7 compare the percentage changes in EUI for each ventilation scenario and location, with VRmid being the reference case. For all ten simulation locations, lower rates of minimum outside air resulted in decreased gas heating energy use. By contrast, with the exception of El Centro and Fresno, reducing outside air from VRmid to VRmin resulted in increased cooling energy use. Table 24 shows the percentage change in site EUI from the reference case VRmid, averaged over the ten equally weighted climate locations.

Table A7-2 shows that the B1B strategy (which provides VRmax ventilation during the daytime operation) provides cooling energy savings for climates with a low number of cooling degree days; the higher ventilation rates were shown to reduce cooling loads using outside-air free cooling in these more moderate climates. Conversely B1B's increase daytime ventilation rates increased cooling energy use in the cooling dominated climates.

Table 24. Percentage change in cooling electricity and heating EUI averaged over study locations, with a constant ventilation rate of VRmid as the reference case

	Ventilation scenario					
	VRMax (A2)	VRMin (A1)	VR min/max (B1)	VR mid/max B2	VR max/min B1B	VR max/mid B2B
Cooling	-6.9%	9.9%	5.2%	-1.2%	-4.3%	-6.0%
Heating	116.2%	-78.1%	-12.8%	39.3%	32.8%	73.5%
Combined	52.0%	-32.2%	-5.0%	17.2%	15.8%	33.2%

Figure 13 and Figure 14 give monthly energy use breakdowns using the VRmid scenario for El Centro and Mount Shasta, representing cooling-dominated and heating-dominated locations, respectively.

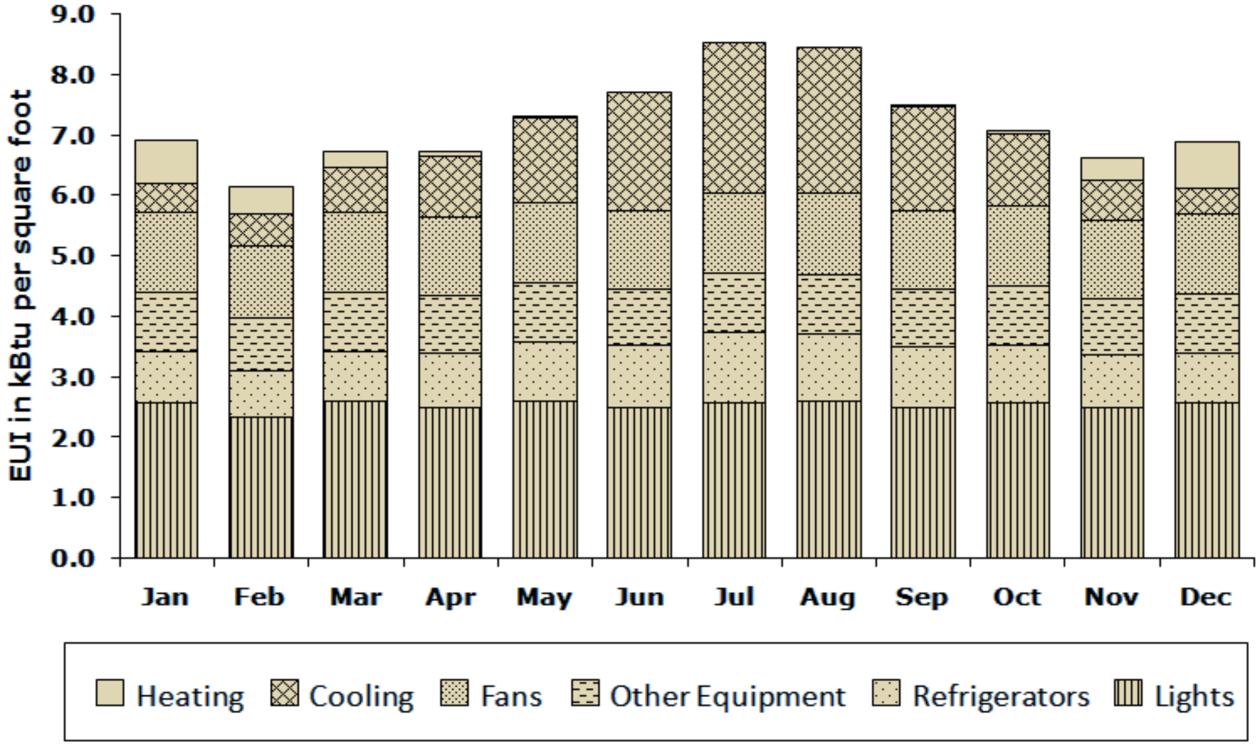


Figure 13. Monthly break-down of energy use for store located in El Centro using VRmid – example of a cooling-dominated location

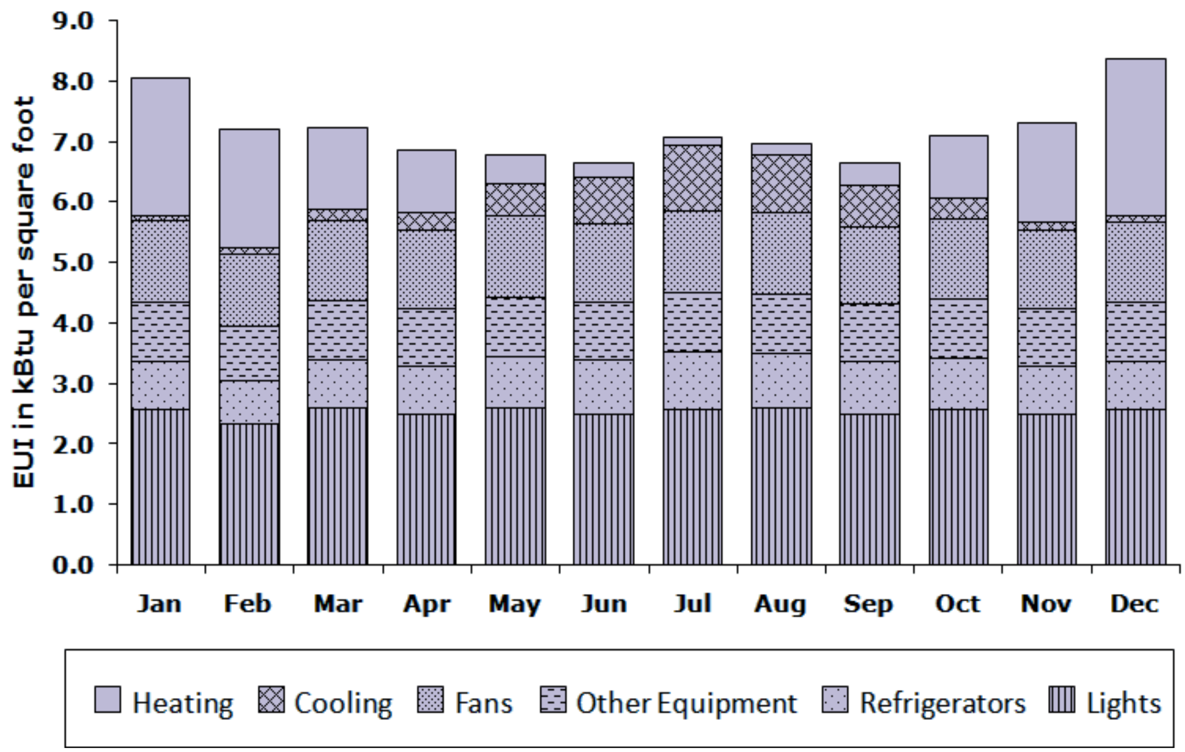


Figure 14. Monthly break-down of energy use for store located in Mount Shasta using VRmid – example of a heating-dominated location

Monthly results demonstrate that internal loads, even during seasonal extremes, dominate energy use in the building. These internal loads result in heat gains to the space that are dominant over the heating gains from gas heating.

Analysis of the monthly variation in heating and cooling energy use for the B-category strategies, revealed that seasonal variation in outdoor temperatures, limit the energy saving potential of any single B category strategy (if used throughout the year), as summer cooling energy savings are counter balanced by winter heating energy cost increases.

Energy simulation results analysis

Attempts were made to compare the building simulation energy use results to building energy use survey data. The EUI break-down by end use was obtained from the Commercial Buildings Energy Consumption Survey (CBECS) data (Energy IQ 2010) for modern retail stores in the Pacific region, between 50k-200k square foot retail floor areas. The CBECS is a survey in the U.S. commercial building stock of energy-related building characteristics, energy consumption, and energy expenditures. This end use breakdown can be seen in Table 25 for both site and source energy.

Significant variations in EUI are seen when commercial buildings are compared across either building activity type or geographic region. However, within the retail building usage category, the size of building has limited impact on total EUI.

Table 25. Energy use breakdown from CBECS, retail store, 1990-2003, Pacific region, 50K-200K sq ft.

Energy location	Major Fuel Energy Intensity EUI (thousand Btu/square foot)							
	Total	Heat	Cool	Fans	DWH	Lighting	All Electrical Equip.	Refrig.
Site	72.1	11	9.4	7.2	1	31.5	2.34	3.3
Source	218.9	13.9	32.4	24.8	1.3	108.6	26.2	11.6

An approximately comparable EUI breakdown by end use was derived from the CEUS database of California commercial buildings. Table 26 gives the breakdown for California retail buildings built since 1991 between 25k-150k square foot.

Table 26. Energy use breakdown from CEUS, Retail warehouse, 1991-present, California, 25K-150K.

Energy location	Major Fuel Energy Intensity EUI (thousand Btu/square foot)							
	Total	Heat	Cool	Fans	DHW	Lighting	All Electrical Equip.	Refrig.
Site	95.9	4.4	10	13.4	3.6	37.8	12.9	13.8
Source	274.5	5.8	31.1	41.9	4.7	117.7	30	43.1

Table 27 gives the breakdown of energy by end use for the Target building, for each of the ten climate zones under the VRmax ventilation scenario. Three climates were identified as being representative of the extremes from the set of climates studied: the Mount Shasta store location has the highest gas heating energy requirement, El Centro the most cooling-dependent location, and the Oakland store both low cooling and heating demands.

Table 27. Energy use breakdown Big Box simulation under VRmax scenario

City location	Climate zone	Major Fuel Energy Intensity EUI (thousand Btu/square foot)							
		Total	Heat	Cool	Fans	DHW	Lighti ng	Electrical Equipment	Refrigerato rs
Arcata	1	86.1	14.0	3.4	15.8	0.0	30.6	11.5	10.9
Oakland	3	84.5	10.3	5.4	15.8	0.0	30.6	11.5	11.0
San Diego	7	82.7	5.6	8.0	15.8	0.0	30.6	11.5	11.3
Pasadena	9	85.2	6.8	9.3	15.8	0.0	30.6	11.5	11.2
Riverside	10	86.8	8.2	9.8	15.8	0.0	30.6	11.5	11.1
Red Bluff	11	91.0	14.2	8.3	15.8	0.0	30.6	11.5	10.7
Sacramento	12	90.6	14.0	7.9	15.8	0.0	30.6	11.5	11.0
Fresno	13	90.5	11.0	10.4	15.8	0.0	30.6	11.5	11.3
El Centro	15	90.7	5.5	16.2	15.8	0.0	30.6	11.5	11.2
Mount Shasta	16	100.5	27.6	5.1	15.8	0.0	30.6	11.5	10.0

The numbers presented in Tables 25-27 have not been standardized to account for differences in ventilation rates between the three disparate sources. A direct comparison between the Target study EUI breakdown by end use and survey data would need to account for differences in the outside air ventilation rate of the survey buildings, compared to the Target model VRmax rate of 1 ACH. However, the comparison does indicate that internal gains from lighting, equipment and fan energy are comparable with retail survey results.

Energy cost analysis

A calculation was made, to a first order approximation, of the dollar costs per store associated with the different ventilation scenarios. Energy costs per unit kW were based on figures from (LBNL 2010), and represent an approximation of current energy costs. A figure of 10 US cents per kWh of delivered electricity and 3.5 US cents per kWh of gas were used to calculate costs. The change in the total facility electricity and gas use, compared to the reference VRmid scenario, are given in Tables A7-4 and A7-5 in Appendix 7. Facility energy costs are for the whole 124,000 square foot store including all retail, stock storage, back office areas, and exterior lighting. The equally-weighed, average difference in energy uses are reported in Table 28, along with a calculation of a dollar cost differential from the reference scenario VRmid.

Table 28. Change in facility annual electricity and gas use for each scenario compared to reference VRmid, and their associated difference in cost.

	Ventilation scenario					
	VRMax (A2)	VRMin (A1)	VR min/max (B1)	VR mid/max B2	VR max/min B1B	VR max/mid B2B
∆Electricity (kWh)	-2.50E+03	5.56E+03	-4.67E+01	-8.33E+02	3.08E+00	-2.58E+03
∆Gas (kWh)	1.91E+05	-1.26E+05	-2.43E+04	6.16E+04	6.23E+04	1.24E+05
∆Cost electricity $	-$250	$556	-$5	-$83	$0	-$258
∆Cost gas $	$6,653	-$4,376	-$844	$2,145	$2,168	$4,328
Total ∆Cost $	$6,403	-$3,821	-$849	$2,061	$2,168	$4,069

Based on these estimates of energy costs, the potential dollar savings from switching from the VRmid (0.6 ACH) to VRmin (0.17 ACH) scenario, averaged over all models, weighted evenly, was a total of $3821 in savings per store. Similarly, a switch from the VRmax (1.0 ACH) to VRmin (0.17 ACH) results in a predicted savings of $10,220 per year per store, reduction from VRmax to VRmid gave a $6,403 savings.

When the B category strategies identified in Table 28 are applied to the set of models across all climate locations, the averaged results, for the most part, identify energy cost increases over the VRmid strategy. However the results presented in Tables A7-1 to A7-3 highlight the importance of climate on the energy use associated with any given ventilation strategy. In addition, analysis of the monthly energy use data identified potential energy cost savings if the ventilation strategy were to be varied, depending on whether cooling energy costs, or heating energy costs, are dominant for that month. Work by Sherman et al. (2004, 2010) previously provided a theoretical basis to support the notion that ventilation load-shifting using an intermittent ventilation strategy can be effective in providing, reduced ventilation energy costs, reduced peak demand energy use and providing some protection from periods of poor outdoor air quality. Sherman developed a simplified method of showing the steady state equivalence of a time varying ventilation rate (Sherman 2010).

Monthly energy use data was used to identify the optimal combination of B1 and B1B for each climate, optimized for energy use costs based on the delivered energy costs identified above. This was repeated for combinations of B2 and B2B; further alternative combinations of the full set of scenarios were not assessed. Table 29 indicates for each month, which of the B type scenarios provided the largest energy cost savings. With the B1B or B2B colored in blue, and the months where B1 or B2 were preferable, colored in red.

Table 29. Ventilation strategy map

KEY	
VRmin/VRmax (B1) or VRmid/VRmax (B2)	
VRmax/VRmin (B1B) or VRmax/VRmid (B2B)	

B1 - B1B												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arcata												
Oakland												
San Diego												
Pasadena												
Riverside												
Red Bluff												
Sacramento												
Fresno												
El Centro												
Mount Shasta												
B2 - B2B												
Arcata												
Oakland												
San Diego												
Pasadena												
Riverside												
Red Bluff												
Sacramento												
Fresno												
El Centro												
Mount Shasta												

By implementing an optimized ventilation strategy specific to climate and dependent on the dominant type of conditioning energy use, significant energy savings were identified. Table 3230 gives the energy and energy cost saving for optimized combinations of the B1-B1B and B2-B2B strategies.

Table 30. Cost savings, with a continuous ventilation rate of VRmid as the reference for optimized combination of category B ventilation strategies.

Optimized for cost

	B1 – B1B	B2 – B2B
∆Electricity (kWh)	-1.84E+04	-1.00E+04
∆Gas (kWh)	-1.23E+05	-1.00E+05
∆Cost electricity $	-$4,291	-$3,486
∆Cost gas $	-$1,837	-$1,001
Total ∆Cost $	-$6,128	-$4,487

These results indicate that these optimized ventilation control strategies result in significant energy cost savings relative to providing a constant ventilation rate at VRmax, VRmid, and even VRmin strategies. Contaminant modeling results indicated that both the B2 and B2B strategies provide improved IAQ compared to the VRmid strategy; with VRmid being shown to sufficiently control individual contaminant level concentrations to below chronic REL levels. The optimized B2 – B2B strategy gave average energy cost savings of $10,694 compared to the VRmax strategy. This optimized B2 – B2B strategy therefore represents a win-win outcome compared to the continuous ventilation rate strategy of VRmid, indicating both improved energy saving and improved IAQ.

Cross study comparisons

NREL study

Recent work by the National Renewable Energy Laboratory (NREL) (NREL 2009) compared building energy simulations of a range of commercial building energy models. The study assessed the energy impact of outside air ventilation on US commercial buildings. Three sets of 4,820 building models were generated to represent the US commercial building stock; US stock upgraded to be compliant with standard 90.1 2004; and a set employing advanced construction practices and building technologies. Weighting factors were applied to the models within each set to scale the study to a national level. The results showed that, for commercial buildings compliant with standard 90.1, the elimination of mechanical ventilation caused an overall 52.5% decrease in outside air ventilation (which includes both infiltration and mechanical ventilation) resulting in a 5.2% decrease in total EUI.

As with this study, for each building model, two simulations were performed, the only difference being that the mechanically-supplied outside air ventilation rate was reduced to zero for one pair of simulations. When in use, outside air ventilation rates for the existing stock group were based on surveyed results from Turk et al. (1989). Minimum ventilation rates for the advanced technology and 90.1 groups were compliant with ventilation rate minimums, as specified in standard 60.1.

The results demonstrated that the minimum mechanical ventilation in the reference models increases the commercial sector average EUI by 6.6%, 5.2%, and 0.7% for the existing stock, 90.1-2004 compliant, and advanced technology groups, respectively. As a consequence of the provision of ventilation, the natural gas EUI was increased by 21.4%, 20.3%, and 8.9%; the electricity EUI's were shown to increase by 0%, 2.8% and 3.1%.

Tables 31 and 32 give the percent change in gas EUI for given percentage change in air change rate, found in the NREL study and this Target store study respectively, for two comparable climate locations.

Table 31. Retail sector percent change in gas EUI by climate zone, comparing standard 62.1 ventilation to no mechanical ventilation scenarios.

DOE Zone	%Change ACH (NREL 2009, T3.8)	%Change in gas EUI 2004-90.1 group (NREL 2009, T3.9)	%Change in electricity EUI, 2004-90.1 group (NREL 2009, T3.10)	%Change in EUI, 2004-90.1 group (NREL 2009, T3.7)
3B	50.6%	17.7%	-4.1%	-0.4%
3C	48.4%	30%	0.5%	2.5%

Table 32. Big Box store percent change in gas EUI by climate zone, from VRmax and VRmid, to VRmin.

VRmid to VRmin.						
City	**California Zone**	**DOE Zone**	**%Change in mechanical ACH**	**%Change in gas EUI Big Box store**	**%Change in electricity EUI Big Box store**	**%Change in EUI Big Box store**
Pasadena, CA	**9**	**3B**	75%	83.8%	-0.1%	3%
Oakland, CA	**3**	**3C**	75%	82.5%	-1.1%	3.6%
VRmax to VRmin.						
City	**California Zone**	**DOE Zone**	**%Change in mechanical ACH**	**%Change in gas EUI Big Box store**	**%Change in electricity EUI Big Box store**	**%Change in EUI Big Box store**
Pasadena, CA	**9**	**3B**	85%	92.6%	-0.34%	6.90%
Oakland, CA	**3**	**3C**	85%	92.2%	-2.0%	9.13%

This comparison highlights that the heat gas energy use for the Target building models was significantly more sensitive to changes in ACH than was found to be the case in the NREL study. This was likely due to significant differences in model assumptions between the broad set of retail buildings used in the NREL study, and the single big box retail model represented in this work.

Significant differences exist between the models used in this study and the NREL study. Firstly, the NREL results presented in Table 31 give results for a range of buildings representative of all non-mall retail buildings. The Target building model is representative of a specific category of large big box retail stores. Secondly, significant differences between the two studies exist in the model assumptions, including differences in HVAC system control; modeling of infiltration; envelope performance; and schedules.

The modeling of unintentional infiltration represented a significant discrepancy between the two studies. In the NREL study, infiltration was modeled as an empirically derived constant average rate for each annual simulation, whereas in this Target store study, it was assumed that, due to the store's positive pressurization, unintentional infiltration would be negligible. Averaged over the whole commercial sector, for the models used in the NREL analysis, infiltration accounted for 31% of the total air change rate; minimum mechanical ventilation accounted for 53% (NREL 2009, T3.2) of the total; and the remaining balance of outside air was introduced by the HVAC system while economizing.

Given these modeling dissimilarities, it is logical that the Target model does not track the behavior of the NREL CBECS based models. Heating gas energy results for the Target model study were found to be significantly more sensitive to outside air ventilation rates than NREL's sector-wide results indicated.

The impact of outside air ventilation on overall whole building energy was found to be comparable for the two studies. In the NREL study, the provision of mechanical outside air was found to result in a 5.2% increase in whole building energy, compared to 4.6% for the Target study.

LBNL Target study

A recent report from LBNL (2010) assessed the effectiveness of a range of energy saving interventions, including a reduction in outside air using the Target P-Store (Haves et al. 2008). Coffey reduced the minimum outside air by 50% for each of seven P-Store Target benchmark models. Averaged over the seven models, the reduced minimal outside air schedule decreased gas heating energy usage by 60.4% and electricity usage by 1.31%, resulting in an overall reduction in averaged total energy use by 7.14%. These results are comparable to the results of this Target study.

Discussion

The goal of this modeling project was to increase the information available for considering an Indoor Air Quality Procedure like that in ASHRAE 62.1-2010 (ASHRAE 2010). Among the specific aims were:

- To develop a more complete list of COCs that we should consider in ventilation standards, based on available information, especially with respect to sources found in big box retail stores, and to assemble available information on levels of these COCs important for health, irritancy, and odor effects.
- To estimate the source strengths for these COCs, in order to allow better estimation of the effects of VRs on indoor concentrations.
- To determine if production of formaldehyde from indoor chemical reactions of ozone was substantial enough to require consideration in ventilation standards.
- From modeling based on the above, to determine which contaminants in big box stores, based on what is known, are likely to be the most important challenges for adequate

control, including some initial consideration of potentially combined effects of related chemicals.

- To assess the influence of increasing VRs, and of different VR schedules, on indoor concentrations of criteria outdoor air pollutants, so that this might be considered in balancing costs and benefits of specific VRs.
- To determine what VR levels or VR schedules might reasonably control contaminants to levels considered acceptable for health, so as to avoid providing excess ventilation that did not produce additional benefits but used energy and increased costs.
- To explore alternative spatial applications of ventilation , such as local ventilation of areas with strong contaminant sources,
- To evaluate the financial and energy costs associated with different levels of ventilation, to allow weighing changes in these kinds of cost against the direct benefits of specific VRs for occupants' health and comfort.

Findings from Contaminant Modeling

We discuss the findings of the specific scenarios modeled:

Scenario A – Ventilation rates kept steady at both VRmax, the current standard, and also VRmid, below the current prescriptive standard, resulted in levels of formaldehyde and other COCs examined below available RELs (Figure 8) and below levels of 10^{-5} excess cancer risk for adult lifetime occupational exposure, per available UREs. In contrast, ventilation at VRmin, a level reported as used currently in some big box stores, produced levels of formaldehyde exceeding the chronic REL (Figure 8) and three COCs including formaldehyde exceeding a 10^{-5} excess cancer risk. VRmin also produced levels of octanal exceeding the olfactory threshold, whereas for VRmid the octanal concentration was 0.33% of the olfactory theshold.

When considering the effects of aldehydes, as examples of compounds with similar modes of action, to be additive, VRmid was marginally able to control contaminant levels adequately. With chronic RELs available for only two of seven measured aldehydes, the summed ratios of concentrations to RELs (called the hazard index) was 0.96, making it plausible that additional available RELS would push that number over 1.0. Furthermore, at VRmid, the model-predicted concentrations of aldehydes collectively approach a joint olfactory threshold. Thus additional data is needed on more compounds to determine if, at ventilation rate VRmid, total aldehyde levels could exceed an effective olfactory threshold for total aldehydes. Note that the hazard indices of multiple substances may not be appropriate to add, so the numbers presented here should be considered only illustrative.

Scenario B – Modeling of Scenario B was conducted to determine if higher VRs at night (e.g., flushing), when cooler air could reduce energy needs and the costs of mechanical cooling , combined with lower VRs in the day could maintain contaminant levels during the day acceptably low, as with constant higher VRs. Results of modeling Scenario B show that levels of formaldehyde, for instance, rise quickly to the concentrations of the lower VR shortly after it is instituted. In the case of VRmid during the day, formaldehyde levels are maintained below the REL, but by a small margin; no COC exceeded a 10^{-5} excess risk of cancer. With VRmin during the day, predicted contaminant levels are not adequately controlled relative to the applicable thresholds.

Scenario C – We modeled the influence of three different steady state VRs on indoor concentrations of outdoor criteria pollutants – two reactive and one non-reactive. The models (Appendix 4.1) suggest little time lag between indoor and outdoor peaks of all these outdoor-generated pollutants. While indoor levels track outdoor levels at all VRs, the relationship of VR to indoor concentration of these outdoor-generated pollutants is opposite of that for indoor-generated contaminants: the higher the VR, the more closely the indoor peaks approach the magnitude of the outdoor peaks. The findings (see plots in Appendix 4.2) suggest that lower VRs delay the increases of indoor concentrations of outdoor pollutants associated with outdoor peaks. These plots suggest that for reactive outdoor air pollutants, and even non-reactive outdoor air pollutants like CO, lower VRs during high ambient pollutant periods and higher VRs during low ambient pollutant periods may result in net protection of building occupants. For reactive outdoor air pollutant gases, the protection that buildings provide for occupants is reduced with higher VRs. For non-reactive ambient pollutants, although the indoor concentration eventually equals that outdoors over a longer time period, lower VRs can reduce peak and average indoor concentrations, which may have health benefits. Thus, the potential adverse influence of higher VRs, with respect to exposures to outdoor-air contaminants, should be considered in assessing the net costs and benefits of specific VRs. Scheduling strategies that consider outdoor-air pollutant patterns seasonally may be helpful. If air cleaning were used for outdoor air brought into a building, this would reduce this type of negative effects of increased ventilation, but add to operation costs.

Scenario D – Models limited to one reactive chemical (ozone), one unsaturated indoor compound (d-limonene), and one product of their indoor chemical reactions (formaldehyde) suggested that the additional amount of irritant chemicals produced (on the order of 0.5-1%) are not meaningful and do not need to be considered in estimating indoor concentrations and required VRs.

Scenario E – Air cleaning, based on the simple models produced here, shows promising potential for reducing indoor concentrations. Given the common systems in which indoor air would make multiple passes through the air handler and an associated air cleaner, even air cleaners with relatively low contaminant removal efficiencies for COCs would substantially reduce indoor COC levels. For instance, even though the indoor concentration of formaldehyde at a constant VRmin, per the models, is over three times the REL, an air cleaner that removes just 20% of formaldehyde per pass , would reduce the indoor formaldehyde concentration to two-thirds of the REL. This suggests that, if air cleaner technology can be developed that removes the key COCs effectively, consistently, and cost-effectively over the long term, air cleaners may allow lower VRs while protecting health and comfort of occupants. Of course, contaminant source reduction by removal of highly emitting materials or products, where feasible and cost effective, is the preferred method for reducing indoor concentrations of contaminants. The practicality of contaminant source reduction in a big box retail store is currently unknown.

Scenario F – Modeling indicated the potential benefits of dividing a store into zones with high and low contaminant emission rates, with an air curtain used to limit air flow between zones.

Adjusting the exhaust flow rates from the two zones to increase air exhaust from the zone with high contaminant emission rates helped to maintain lower indoor contaminant concentrations in both zones . . On the other hand, the more air that flows from the high-emission to the low-emission zone (e.g., if the spaces are not separated or the ventilation system mixes the air), the higher the concentrations in the low-emission zone. Thus, if almost no air is allowed to flow from the high-emission zone to the low-emission zone, and almost all of the exhaust from the low-emission zone flows into and to outdoors through the high-emission zone, with ventilation rate VRmid, the modeled indoor concentration of formaldehyde in the high-emission zone is just under the REL (8.8 µg m^{-3}), while that in the low-emission area is less than one-third of the REL (2.6 µg m^{-3}). If it is desirable to achieve similar concentrations throughout the building interior, then more mixing of air from the high-emission zone into the low-emission zone will produce that, although this does substantially raise levels in the low-emission space; e.g., from 8.8 and 2.6 µg m^{-3} to 8.6 and 4.7 or even to 8.4 and 7.5 µg m^{-3}. Thus, the strategy seems to be effective, given the limits of the modeling, and the remaining issues are partly technical – how to achieve this technically in an actual store, in terms of distribution of contents, separation of indoor air between spaces – and partly non-technical – how should indoor concentrations in the store be distributed. A reasonable approach might be to minimize total human exposure or risk assuming equal density of occupancy in multiple spaces.

Scenario G – We did not perform modeling of displacement ventilation.

Overall, results from the contaminant models suggest that with VRmax, concentrations of the COCs examined do not exceed chronic RELs or known olfactory or irritant thresholds. With VRmin, concentrations of formaldehyde exceed the chronic REL, and those of octanal exceed the olfactory threshold. VRmid, halfway between these two, does not produce concentrations that exceed available chronic health, olfactory, or irritant thresholds; however, when considering even one group of compounds, the aldehydes, as having additive effects, VRmid succeeds just marginally in staying below thresholds for chronic health and olfactory effects. Varying VRs with lower daytime rates and higher night-time flushing did not seem promising as an energy-saving strategy. Indoor chemical reactions, to the limited extent considered here, do not seem to be an important factor for estimating indoor concentrations, at least of formaldehyde.

Consideration of the entry of outdoor air pollutants as affected by ventilation rate will be an important factor in weighing costs and benefits of changes in VR standards. Air cleaning is promising as a way to make lower VRs consistent with acceptably low indoor contaminant concentrations, depending on the cost and long-term feasibility and reliability of technology to remove all COCs. Local ventilation in a contained zone near strongly emitting sources of key contaminants also shows promise as a way to allow lower general VRs in areas with lower emissions; one challenge would be to jointly configure contents, space separation, and ventilation systems to achieve this goal. Displacement ventilation, based on prior work, does not seem promising as a strategy to increase ventilation effectiveness in big box stores and allow reduced outdoor air VRs.

In considering the adequacy of lowering allowable ventilation rates in big box stores, it is important to consider two additional questions, not covered in this paper, but which can be evaluated in the larger amount of research findings available from commercial office buildings. These are the questions of whether VRs at the current prescriptive level actually satisfy the requirements of ASHRAE 62.1-2010 with respect to occupant satisfaction with indoor air, and whether these VRs adequately protect occupants' health. Answering these questions requites a more direct and comprehensive evaluation of emissions, and associated health, odor, and irritancy effects) from all indoor contaminants, whether produced by the building, the ventilation systems, the contents and equipment, or the occupants. The following conclusion about these questions, and the associated dilemma, was summarized in the report from the second part of the current CEC project (Mendell and Apte 2010):

> "Current commercial buildings, designed and operated per VRP [ventilation rate procedure] specifications, are not now providing occupants with the quality of indoor air implicitly promised by the standards. [Note – this is roughly equivalent to the VRmax level assessed in this paper on big box stores.] Commercial buildings in both the U.S. and Europe, given current building features, contents, occupants, and ventilation rates, do not provide air considered acceptable by a sufficient proportion of occupants. Furthermore, ventilation rates above current minimum guideline levels significantly reduce health symptoms in occupants, and these benefits do not begin to taper off until substantially higher levels than the current recommended minimum, implying that current recommended ventilation levels allow levels of indoor pollutants that increase symptoms in occupants. Dramatically increasing ventilation levels as a solution, however, seems too costly and energy-intensive, still might not adequately reduce indoor pollutants of concern, and in some locations would substantially increase existing problems with intake of highly polluted or humid outside air."

Findings from Energy Modeling

In the ten locations tested with diverse California climates, heating and cooling energy represented a significant proportion of the annual energy use of the building model, ranging from a combined total of 11% of the whole building energy use, in Oakland and San Diego, up to 21% in Mount Shasta. For all climates studied, heating gains to the space were shown to be primarily driven by internal gains from lighting, fan energy, and equipment energy use. This resulted in significant cooling energy demand throughout the year in all climate zones studied.

The study indicated that use of gas heating energy was significantly more sensitive than use of electrical cooling energy to changes in ACH rates. This was also found to be the case in previous NREL and LBNL studies.

Results from the Target study of energy use were compared with survey data from the CEUS and CBECS databases. Comparisons indicated that whole building energy; lighting, ventilation fan energy, and electrical equipment seem to be roughly in line with the retail averages found in the surveys of measured energy use breakdowns.

For all ten simulation locations, lower rates of minimum outside air resulted in decreased gas heating energy use. By contrast, with the exception of El Centro and Fresno, reducing outside air from VRmid (0.60 ACH) to VRmin (0.17 ACH) resulted in *increased* cooling energy. When using a continuous ventilation rate of 0.17 ACH compared to 0.60 ACH, combined gas heating and electric cooling EUI was 32% lower; however, this 75% reduction in mechanical outside air ventilation was associated with whole building energy EUI only 4.6% lower. Studies by LBNL and NREL have reported comparable findings for the impact of outside air ventilation on whole building energy. A reduction in outside air ventilation rates from VRmax (the rate prescribed by the Standard 62.1 VRP) to VRmin (a rate assessed for potential use in Target stores), resulted in a 10.9% reduction in total site energy. This equally-weighted average reduction in site energy of 10.9% represents a savings of $10,220 per year per store. For a change in the ventilation rate from VRmax to VRmid a 6.63% reduction in total energy resulted in a $6403 dollar saving. A full analysis including population weighting would be necessary to assess the impact to California; however this is beyond the scope of this project.

The monthly energy use results indicated that the energy saving potential of reduced outside air ventilation is highly dependent on the climate and season. Deploying any single ventilation strategy across big-box-retail stores throughout California is likely to miss the significant energy saving potential of a more tailored ventilation strategy. By making use of nighttime ventilation cooling during the summer in hot climates, and lower daytime ventilation in cold climates during winter, significantly greater energy savings can be achieved compared to providing continuous reduced ventilation levels. Alternative low energy ventilation schedules were developed for each climate zone, based on optimized combinations of the B1-B1B or B2-B2B strategies. The results showed that by applying a ventilation strategy that is optimized for each climate location, significant energy cost savings can be achieved while also maintaining acceptable IAQ. The optimized B2 – B2B strategy was found to give an average energy cost savings of $10,694 compared to the VRmax strategy.

Combined Findings of Contaminant Modeling and Energy Modeling

The energy models estimate that, in California overall, lowering VRs in big box stores from VRmax to VRmid would produce a relatively small proportional decrease in total building energy use intensity. Deploying a continuous ventilation strategy across big-box-retail stores throughout California is unlikely to achieve the energy saving potential of a more tailored ventilation strategy that considers both climate zone and seasonal variations. Still, considering the total amount of energy involved, the magnitude of potential savings in costs and energy would still be substantial. Thus, reducing the required minimum VRs in big box stores in California has potential to produce a meaningful, if not proportionally large, reduction in energy use and energy-related costs. The challenge would be to do this in a way that protects the health and comfort of occupants of these buildings, including workers and customers. One potential strategy to assist both these objectives is to use intermittent ventilation strategies to flush out contaminants when the cost of ventilation is at its lowest during the daily cycle. Night time ventilation can provide some free cooling while removing contaminants that would otherwise build up and require increased day-time ventilation. Lower heating set-point temperatures in the store at night provide opportunities at certain times to ventilate with a potentially lower associated heating energy penalty. Findings from the various types of contaminant models produced in this project, combined with findings from a prior review of evidence about the adequacy of current prescriptive standards, suggest the following:

- When using ventilation rates marginally lower than the current prescriptive VR standards in big box stores, it seems possible to maintain levels of COCs below available chronic non-cancer and cancer health, olfactory, and irritant thresholds for individual substances. However greater energy savings can be achieved using a more considered ventilation strategy, while still maintaining acceptable IAQ.

- Even a limited consideration of the combined effects of related indoor contaminants suggests that reduced VRs meeting the criteria in the prior bullet may not meet these more complex criteria.
- Similarly, the availability of increased information on chronic health, odor, and irritancy effects for indoor contaminants seems likely to increase the minimum VRs required.
- Considerations of measured health effects and acceptability of indoor air in big box stores, requiring new data collection, may further increase the minimum VRs required to achieve the requirements of ASHRAE 62.1-2010, based on parallel data available from office buildings.
- Potential entrainment of ambient pollutants are an important concern in balancing costs and benefits of specific VR standards, particularly in areas with high levels of ambient pollution. Air cleaning may be required to achieve acceptable solutions.
- *Increased* ventilation may not be the solution to improving health and acceptability in office buildings with current prescribed VRs; source removal, air cleaning, and local ventilation may be the solution in these buildings as well as in big box retail stores, and these strategies may also allow improved health and acceptability with reduced VRs in both kinds of building uses.

Limitations

The findings from this project have a number of limitations. The simple one- and two-compartment mass-balance models used do not accurately represent the emissions and mixing behavior in a real store or all stores. Whole building emissions factors used in these models were estimated from a limited number of reports, which came at best from settings very similar to those we intended to model, but in other cases from different kinds of commercial buildings. For many of the contaminants considered, we had insufficient data on health, olfactory, or irritancy thresholds. Many additional chemicals present in big box retail environments are undoubtedly missing from our analyses because sufficient data were not available. We consider the analyses presented here to provide only an initial attempt to characterize emissions, ventilation, and concentrations of contaminants in big box commercial stores, in order to draw preliminary conclusions and to highlight additional data that are still needed.

Summary and Conclusions

This paper summarizes and interprets the findings of a variety of modeled simulations of ventilation strategies in a big box store. The energy models estimate that, in California overall, lowering VRs in big box stores from VRmax to VRmid would produce a meaningful, if not proportionally large, reduction in energy use and energy-related costs. The challenge would be to do this in a way that protects the health and comfort of occupants of these buildings. Findings from the various types of contaminant models produced in this project, combined with findings from a prior review of evidence about the adequacy of current prescriptive standards, suggest the following: The provision of ventilation rates that are marginally lower than the current prescriptive VR standards in big box stores could maintain levels of COCs below available chronic health, olfactory, and irritant thresholds for individual substances; however, consideration of the combined effects of related indoor contaminants is likely to increase the minimum VR levels required. Furthermore, the availability over time of increased information on chronic health, odor, and irritancy effects for indoor contaminants seems likely to suggest increases in minimum VRs in a variety of building types. Ultimately, if even current prescriptive VRs (roughly equivalent to VRmax in this report) were shown to be inadequate for providing desired indoor air quality in commercial buildings, further increased ventilation might be neither an effective nor a feasible solution; source removal, air cleaning, and local ventilation, combined with moderate ventilation rates, may be the best strategies. Strategies such as these are likely to be necessary to provide the desired indoor air quality with *reduced* VRs, and possibly even with the ventilation rates in current standards..

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