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Evaluation of the Indoor Air Quality Procedure for Use in Retail Buildings

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ABSTRACT

California's building efficiency standards (Title 24) mandate minimum prescribed ventilation rates (VRs) for commercial buildings. Title 24 standards currently include a prescriptive procedure similar to ASHRAE's prescriptive "ventilation rate procedure", but does not include an alternative procedure, akin to ASHRAE's non-prescriptive "indoor air quality procedure" (IAQP). The IAQP determines minimum VRs based on objectively and subjectively evaluated indoor air quality (IAQ). The first primary goal of this study was to determine, in a set of California retail stores, the adequacy of Title 24 VRs and observed current measured VRs in providing the level of IAQ specified through an IAQP process, The second primary goal was to evaluate whether several VRs implemented experimentally in a big box store would achieve adequate IAQ, assessed objectively and subjectively.

For the first goal, a list of contaminants of concern (CoCs) and reference exposure levels (RELs) were selected for evaluating IAQ. Ventilation rates and indoor and outdoor CoC concentrations were measured in 13 stores, including one "big box" store. Mass balance models were employed to calculate indoor contaminant source strengths for CoCs in each store. Using these source strengths and typical outdoor air contaminant concentrations, mass balance models were again used to calculate for each store the "IAQP" VR that would maintain indoor CoC concentrations below selected RELs. These IAQP VRs were compared to the observed VRs and to the Title 24-prescribed VRs.

For the second goal, a VR intervention study was performed in the big box store to determine how objectively assessed indoor contaminant levels and subjectively assessed IAQ varied with VR. The three intervention study VRs included an approximation of the store's current VR [0.24 air changes per hour (ACH)], the Title 24-prescribed VR [0.69 ACH], and the calculated IAQP-based VR [1.51 ACH]).

Calculations of IAQP-based VRs showed that for the big box store and 11 of the 12 other stores, neither current measured VRs nor the Title 24-prescribed VRs would be sufficient to maintain indoor concentrations of all CoCs below RELs. In the intervention study, with the IAQP-based VR applied in the big box store, all CoCs were controlled below RELs (within margins of error). Also, at all three VRs in this store, the percentage of subjects reporting acceptable air quality exceeded an 80% criterion of acceptability.

The IAQP allows consideration of outdoor air ventilation as just one of several possible tools for achieving adequate IAQ. In two of the 13 surveyed buildings, applying the IAQP to allow lower VRs could have saved energy whilst still maintaining acceptable indoor air quality. In the remaining 11 buildings, saving energy through lower VRs would require combination with other strategies, either reducing indoor sources of CoCs such as formaldehyde, or use of gas phase air cleaning technologies. Based on the findings from applying the IAQP calculations to retail stores and the IAQP-based intervention study, recommendations are made regarding the potential introduction of a comparable procedure in Title 24.

INTRODUCTION

The goal of reducing the energy use of commercial buildings, while maintaining acceptable air quality, is shared by building operators, employers, governmental bodies and researchers alike. Significant progress has been made in recent years in improving building energy performance through a combination of mandated standards, technology advances, and recommendations provided by non-governmental organizations such as ASHRAE and the U.S. Green Building Council.

One area that has received significant attention is the minimum requirement for ventilation (outdoor air supply) in commercial buildings. The heating and cooling needed to condition ventilation air makes up a small but significant portion of the total energy consumed by commercial buildings (Benne, et al. 2009). However, ventilation is also essential in providing healthy, productive working environments for building occupants (Sundell, et al 2011, Seppänen, et al 2004). ASHRAE Standard 62.1-2010 (ASHRAE 2010) provides two alternative procedures for selecting minimum (VRs) for commercial buildings. In the "ventilation rate procedure" (VRP), users adopt the minimum VRs listed in a table, with indoor air quality (IAQ) assumed to be acceptable at this VR, regardless of the building's features. The prescribed minimum VRs differ by building use, and are the sum of two quantities: the minimum rate of outdoor air supply per unit floor area, and the minimum rate of outdoor air supply per occupant. These prescribed rates were based historically on the rates needed to maintain satisfaction with odors from occupants, and more recently have in limited ways considered indoor emissions from both occupants and the building itself. The VRP provides definitive guidance on minimum VRs that can be used to specify HVAC system sizing during the design phase of a new building.

Standard 62.1 also includes an alternative (and rarely used) "indoor air quality procedure" (IAQP), with both objective and subjective components, intended to provide greater flexibility that may enable energy savings. In contrast to the VRP, the IAQP is a performance-based design approach that does not prescribe specific VRs by building use. The IAQP allows flexibility in the means to achieve adequate levels of IAQ, including outdoor air ventilation, source control, air cleaning, or other strategies. Application of a comprehensive IAQP protocol (including both objective and subjective assessments of IAQ) is performed in stages, with the final stages occurring after the building is constructed and occupied. The first step in the IAQP is to specify a set of contaminants of concern (CoCs), and, based on guidelines from cognizant authorities, associated indoor reference exposure levels (RELS) not to be exceeded. Users of the IAQP are free to select which contaminants are considered and which guidelines should be used to determine their maximum concentrations. To satisfy the objective component of the IAQP, indoor (and outdoor) emission rates of all CoCs are calculated based on estimated building materials and contents. An overall ventilation and design strategy must then be identified that will maintain indoor concentrations of all CoCs below RELs. VRs lower than those specified in the VR procedure are allowed, as long as the designer can demonstrate that CoC concentrations are below selected RELs. Once this strategy is applied, and the building is constructed and occupied, a subjective test of the perceived air quality is performed to demonstrate that visitors and/or occupants are "satisfied" with the air quality. The IAQP does not describe the procedure for assessing satisfaction with air quality or the level of satisfaction that must be provided. Subjective assessments of IAQ are normally based on survey responses, collected either from occupants after a period of time in the building (adapted responses) or from panels of simulated visitors immediately after they enter the building (unadapted responses).

The IAQP is designed to allow the minimum VR that will verifiably maintain acceptable IAQ, without over-ventilating and wasting energy. While the IAQP may allow VRs to be reduced relative to those required by the VR procedure, application of the IAQP in some circumstances may require higher VRs. Although the IAQP has been used to a limited extent, at least one large retail organization uses the IAQP to specify the minimum ventilation requirements for its stores throughout the U.S. In this case, the applied IAQP-based VR rates were significantly lower than the alternative prescribed rates. It is unclear whether building owners or designers would ever voluntarily design or operate a building with alternate IAQP-based VRs that exceed the minimum prescribed VRs, thus achieving improved IAQ at a greater energy cost.

In California, there is ongoing consideration of the merit of incorporating an IAQP-like procedure into the state's Title 24 building efficiency standards (CEC 2008). A recent report details some of the limitations of the current IAQP in ASHRAE 62.1-2010 (Mendell and Apte 2012). The report also describes some limitations of standards which prescribe fixed minimum VRs, which are assumed to provide adequate IAQ but do not consider building features such as the use of air cleaning equipment or the strength of indoor pollutant sources.

This study had two main goals: (1) to determine, in a set of California retail stores, the adequacy of VRs currently prescribed by Title 24, and also of the observed current VRs, in providing the level of IAQ specified through an IAQP process; and (2) to evaluate whether several VRs implemented experimentally in a big box store, including the current VR, the Title 24-prescribed VR, and a calculated IAQP-based VR, would achieve adequate IAQ, assessed objectively and subjectively.

Two types of data were collected to evaluate the IAQP in California retail buildings; observational data from stores functioning as usual, and data from an intervention study in a single big-box store.

Through the process of applying the IAQP, the research team also developed specific recommendations for potential future California ventilation standards based on IAQ. This study provides necessary data to the discussion of adding an IAQP-like option to Title 24.

STUDY METHODS

For the first goal, a list of contaminants of concern (CoCs) and reference exposure levels (RELs) were selected for evaluating IAQ. Ventilation rates and indoor and outdoor CoC concentrations were measured in 13 stores, including one "big box" store. Mass balance models were employed to calculate indoor contaminant source strengths for CoCs in each store. Using these source strengths and typical outdoor air contaminant concentrations, mass balance models were again used to calculate for each store the "IAQP" VR that would maintain indoor CoC concentrations below selected RELs. These IAQP VRs were compared to the observed VRs and to the Title 24-prescribed VRs.

For the second goal, a VR intervention study was performed in the big box store to determine how objectively assessed indoor contaminant levels (from measured air concentrations) and subjectively assessed IAQ (from subject surveys) varied with VR. The three intervention study VRs included an approximation of the store's current VR [0.24 air changes per hour (ACH)], the Title 24-prescribed VR [0.69 ACH], and the calculated IAQP-based VR [1.51 ACH]).

First, a list of CoCs and RELs to consider in evaluating IAQ was constructed. Potential CoCs included, 1) VOC's and aldehydes previously identified in commercial-building indoor environments, 2) particles, 3) ozone, and 4) carbon monoxide. The VOCs and aldehydes that were CoCs were identified by Parthasarathy, et al (2012). Reference exposure levels (8-hour RELs) were identified for each CoC, where available, from lists of RELs from California's Office of Environmental Health and Hazard Assessment (OEHHA). Where no OEHHA reference level existed, RELs from alternative cognizant authorities were referenced; these included the US Environmental Protection Agency (EPA), the National Institute for Occupational Safety and Health (NIOSH), and the Agency for Toxic Substances and Disease Registry (ATSDR). Odor thresholds were used in addition to exposure levels as these are relevant to perceived IAQ (Fanger**,** 1988). Thresholds for VOC odor and pungency used were obtained from Cain and Schmidt (2009), Hodgson et al. (2003a) and Nagata (2003). The lowest thresholds among these studies were selected to screen compounds of concern (Parthasarathy, et al 2012).

Observational Field Study Methods

Ventilation rates and, simultaneously, indoor and outdoor CoC concentrations were measured in 13 California retail stores, including one "big box" store. Full details on methods and the data collected are described in Chan, et al. (2012), with one significant difference being that particle mass measurement was performed during the intervention study in the big box store, but not during the baseline observational study.

For each CoC indoor source strengths were first calculated based on measured indoor and outdoor contaminant concentrations and the measured VRs.

Indoor source strengths of VOC CoCs were calculated in each store, using a simple mass balance model, with VRs and indoor and outdoor contaminant concentrations used as model inputs. Where multiple periods of sampling were performed, source strength was calculated for each sampling period, and an average emission rate calculated. Appendix A1 details the mass balance model used to calculate VOC source strengths.

Indoor particle concentrations were assumed to be a combination of indoor-generated and outdoor-sourced particles. In order to estimate indoor particle emission rates, it was first necessary to estimate the fractions of indoor air particles that originated from indoor sources and from outdoors, taking into account particle removal by filtration. A mass balance model was used with measured field data from each store, to estimate the relative proportions of indoor- to outdoor-sourced particles. Measured 8-hour cumulative samples of indoor and outdoor particle mass, particle removal efficiencies of the filters based on the filter efficiency ratings, measured ventilation rates, estimates of rates of air recirculation through filters, and published values of particle removal rates by deposition on surfaces were all used as inputs into our mass balance model. This model was then used to provide estimates of indoor particle mass source strengths. Appendix A2 provides further details on the calculation methods. Because of the uncertainties in estimating particle removal by filters, the uncertainties in indoor particle source strengths are larger than the uncertainties in sources strengths for gaseous contaminants.

Using calculated indoor CoC source strengths, and typical outdoor air contaminant concentrations for each store, mass balance models were used to calculate an "IAQP" VR that would maintain indoor particle and VOC CoC concentrations below selected RELs. Where ventilation could not maintain concentrations below the RELs, because outdoor contaminant concentrations already exceeded RELs, alternative methods of meeting RELs were evaluated.

Alternative strategies include source control measures to lower CoC emission rates by a given percentage, or increased particle filtration.

Levels of average concentrations of indoor VOC's and aldehydes were compared to the relevant RELs. A subset of these contaminants was identified for each store, based on whether the indoor concentrations approached or exceeded RELs. The minimum VRs necessary to maintain concentrations below RELs were then calculated for this limited number of store-relevant VOC CoCs. IAQP-based VRs were compared to the observed VRs and the Title 24-prescribed VRs. A detailed IAQP calculation method for VOC's can be found in Appendix A1.As an alternative to increased ventilation, a calculation was made of the percentage reduction in indoor contaminant emission rates required to lower indoor concentrations to below RELs, assuming prescribed title-24 VRs. The source control calculation method is detailed in Appendix A2. The final IAQP-based VR for each store was based on the results of this analysis of VOC and aldehydes, and the analysis of particle contaminants detailed below.

Using the estimates of indoor particle mass source strengths, mass balance models were then used to assess the impact of various VRs on indoor particle concentrations in each study building. For the six naturally ventilated stores, models did not include particle filtration and assumed additional ventilation was provided by windows or open doors. Reference outdoor particle concentrations used as a model inputs, were based on four-year state annual "worse case" outdoor concentrations of PM 2.5 and PM 10 (ARB 2012b). Reference outdoor concentrations for each study building varied by county and are listed in Table 1. Where possible, a VR was identified that would limit indoor particle concentrations to below CA guideline levels.

Even if VRs are able to maintain indoor contaminant concentrations below RELs, the IAQP also allows for alternatives to ventilation as a means of keeping indoor contaminant concentrations below reference levels. Air cleaning or contaminant source control, are both acceptable means of lowering indoor concentrations of contaminants, and can be applied either by themselves, or in tandem with ventilation. In the seven buildings with mechanical ventilation, mass balance models were used to calculate the minimum filtration efficiency required to limit indoor particle concentrations to CA EPA annual guidelines. For buildings where indoor particles were predominantly from indoor sources, an estimate was made of the percentage reduction in indoor generated particle required to meet RELs, assuming Title-24 ventilation rates. Because of uncertainties, particularly in the rates of particle removal by filters, the IAQP-based VRs for particles have a larger uncertainty than the IAQP-based VRs for VOCs and aldehydes. A detailed calculation method can be found in Appendix A3 provides detailed calculation methods for the IAQP-based VR calculation rate, filtration and source control strategies.

Intervention Field Study Methods

A VR intervention study was performed in the big box retail store included in the 13 studied stores. The Big Box store, located in northern California, has a single story and a sales floor area of 10,000 m^2 within one large open room. The ceiling height is 4.2 m, above which there is a 3 m high plenum. A very broad range of products are available in the store, including clothing, house wares, groceries, toys and sporting goods and various other categories of products. Included within the main retail area are a small fast food outlet and a chain coffee retail outlet, which are potential sources of combustion generated pollutants. Thermal conditioning is provided by five conventional variable air volume (VAV) roof top units (RTUs) with economizers and an additional fan-powered exhaust system. An experimental evaporative cooling unit is also currently installed and operational at the store, providing additional ventilation air.

Three VRs were implemented: a low rate approximating the store's current VR [0.24 air changes per hour (ACH)], a medium rate based on the Title 24-prescribed VR [0.69 ACH], and a high rate based on the calculated IAQP-based VR [1.51 ACH]). The store's VRs were fixed for one week study periods at each of these three rates. In each study period, IAQ was assessed objectively, by measuring indoor contaminant concentrations, and subjectively, with surveys of perceived air quality and acute health symptoms.

Environmental measurements in the intervention study

For each one-week study period, concentrations of a range of indoor contaminants, including volatile organic compounds (VOCs), particles, and inorganic gases were monitored at up to four locations within the store and one location on the roof. Indoor sampling stations were located approximately central to each of the four store quadrants, at height of between 1.4 and 1.8 meters, subject to availability of shelve space and electrical power. Indoor and outdoor ozone concentrations were monitored in real time using three 2BTech ozone monitors (Model 205). Particle counts were monitored over a range of particle sizes using: three MetOne optical particle counters; Model BT-637 with six particle size channels (>0.3, >0.5, >0.7, >1, >2, and >5 μm); three TSI DustTraks with a size selective inlet (<2.5 μm); and twoTSI WCPC 3781 water based condensation particle counters (0.006 to 3 μm). Particle mass was measured by sampling onto polytetrafluoroethylene (PTFE) membrane filters, which were weighed in a temperature and relative humidity controlled enclosure. Particle mass less than 2.5 micrometers (PM2.5) and less than 10 micrometers (PM10) were measured using SKC Personal Environment Monitors at 10 litres per minute (Lpm)for approximately 8 hours, to collect particle samples on membrane filters. The mass difference of the filters pre and post sampling, and sample volumes were used to calculate particle mass concentrations. Two field blanks were collected on each sampling day. Measurement error was 1μg, or approximately 0.3 $\mu g/m^3$for an 8-hour sample.

An Environmental Gas Monitor by PPSystems (EGM-4), calibrated with primary standard calibration gases, was used to continuously monitor indoor CO_2 concentrations over the study period. Multi-sorbent tubes containing Carbopack B and Carbopack X were used to capture VOCs with a range of different vapor pressures. Volatile carbonyl samples were collected using dinitrophenyl hydrazine (DNPH)-coated cartridges (Waters Sep-Pak®). Ambient ozone was removed with potassium iodide scrubbers preceding each DNPH sampler. One-hour samples were collected at each of the four indoor and single outdoor locations at 1 Lpm, using a novel low-cost sampling system developed specifically for the study. Multiple samples were collected immediately following a change in the study ventilation rate and then periodically throughout the remainder of each study. Four sorbent tube samples (two DNPH and two Carbopak) were collected simultaneously to provide duplicates of each sample type. Thermal desorption-gas chromatography/mass spectrometry was used to quantitatively analyze the VOC samples by following U.S. EPA Methods TO-1 and TO-17 (U.S. EPA 1984, 1999). Multi-point internal standard calibrations were performed using pure compounds and 1-bromo-3-fluorobenzene as the reference compound. A duplicate set of samples was collected at all times. DNPH cartridges were extracted with 2-mL aliquots of acetonitrile, and the extracts were analyzed by high performance liquid chromatography (HPLC) with UV detection at λ_{max} = 360 nm (Agilent 1200).

A calibration curve for quantification was carried out using authentic standards of the formaldehyde-DNPH hydrazone.

Prior to the intervention study in the Big Box store, measurements established an approximate relationship between mechanical damper configurations and measured VRs. This relationship enabled selection of the damper settings and fan speeds to produce the desired three VRs, at the beginning of each week of the subjective response study.

Whole building VRs were measured with a tracer gas decay procedure. Small volumes of sulfur hexafluoride (SF_6) tracer gas were injected directly into the outside air inlets of all six of the store's main air-handling units, producing indoor concentrations of approximately 1.5 parts per million (ppm). Injections occurred simultaneously over a period of several minutes, using a system of delivery tubes connected to valves, calibrated to produce approximately homogeneous concentrations in the store. Through normal operation of the air handling units, fresh outside air (that did not include tracer) gradually replaced the store air that contained the tracer gas, causing the concentration of tracer gas to decay. Tracer gas concentrations were measured for period of approximately 1 hour to coincide with the VOC sampling. Tracer concentrations were measured using Miran SapphIRe® Model 250B infrared gas analyzers, calibrated with primary standard calibration gases. An earlier calibration study of the Miran SappahIRe® found the instrument responded linearly over a range of PFT concentrations of 100 to 1500 ppb. VRs were calculated using the age of air calculation method (ASHRAE 1997) using tracer concentration decay data from within this 100 to 1500 ppb range. The average VR for each sample collection period was given by the reciprocal of the average of the age of air, at the four stations.

Subjective measurements in the intervention study

Perceived IAQ was subjectively assessed in the Big Box store, using three independent groups of untrained human subjects. During each of three study weeks, store VRs were held constant to the degree possible by deactivating outdoor air economizer controls, maintaining constant fan speeds, and maintaining constant damper settings for outdoor, re-circulated, and exhaust airflows for a several day period.

Once steady state indoor contaminant concentrations were achieved after each VR transition, subjects took a series of surveys. Subjects were given a set of six identical paper-based surveys to be completed at six allotted times, at specific locations in the store identified by six station markers. Survey questions assessed olfactory responses and short-term health-related symptoms. All subjects entered the store and took the initial survey (#1) at the same location. They performed this first of six surveys immediately after entering the store, to assess perceived air quality and symptoms before their olfactory responses became adapted to the store environment. Subjects then performed a predetermined sequence of four surveys, one in each of the store's four quadrants (#2-5). Each of these four adapted surveys was preceded by a 12 minute period of adaption to the local air within the store, achieved by walking around within the predefined quadrant. The order of quadrants in which subjects took these four surveys was balanced to reduce any bias associated with local variations in store environments. The last adapted survey (#5) was performed by all subjects near the main entrance. The final survey (#6) was performed after subjects had exited the store for three minutes to refresh their olfactory systems, and returned to the survey station near the main entrance, for a second unadapted survey at the same location (#1) as the first. Figure A18 in Appendix C shows the map provided to subjects with an example of an assigned route connecting the identified survey station locations.

Appendix C, Figure A19 is an example of a single two-page survey that subjects completed at station one. In addition to the surveys, subjects also answered questions to provide demographic data, including their age, gender, employment status, income range, and marital status. A set of health factors and shopping habits were also assessed: whether the subject smoked, had ever been diagnosed with asthma, and had any of a list of common allergies. Because this study included human subject research, a human subject protocol was developed, reviewed, and approved by Lawrence Berkeley National Laboratory's Committee for the Protection of Human Subjects.

In response to the survey questions on olfactory responses and subjective symptoms, subjects were free to mark their perceptions, using a pen, anywhere along a (horizontal or vertical) linear scale. An example is shown in Figure 1.Survey responses were translated manually to electronic data by measuring the distance of each response from the left side of the scale (or the bottom of the scale for vertically oriented scales). In a quality assurance check, 20% of the surveys were measured and digitized again by a different person, and the results compared, with no significant differences in scale readings.

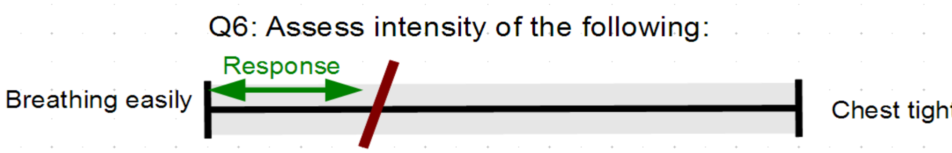

Figure 1.Survey response example.

In response to the question "How do you rate the air quality?" subjects were free to mark anywhere along either (but not both) of two scales that ranged from "Clearly unacceptable" to "Just unacceptable" or from "Just acceptable" to "Clearly acceptable". Subject's responses were translated into a numerical scale ranging from -1 to 0 representing unacceptable responses and 0 to 1 for acceptable responses. (Note: there were no responses at 0 on either the acceptable or unacceptable scale.) In addition to this continuous scale, responses were also simplified into a binary scale of "unacceptable" or "acceptable", depending on which of the two scales subjects marked their response. Surveys one and six were administered to subjects immediately after entering the store from outside, and were therefore provided unadapted responses. Surveys two, three, four and five, taken after subjects had been in the store for at least 12 minutes, provided adapted responses. Analysis was performed separately for adapted and unadapted responses.

The responses to air quality surveys were plotted against several demographic, health, and environmental variables. Temperature and humidity were considered potential confounding variables in the relationship of VR to air quality and symptoms; however, the influences of temperature and humidity could not be separated from that of ventilation, as each of the three study VRs had one period, which had single associated values for average humidity and temperature. Survey responses were then used to determine if the changes in VRs caused statistically significant changes in perceived air quality and short-term health symptoms. Two-sample T-tests, assuming equal variance of response, were used to explore potential confounding variables of the relationship between ventilation rate and acceptability of air, such as gender, asthma status, and allergy status. A key objective of this analysis was to determine whether our air quality satisfaction target was achieved (as required by the IAQP) at each VR level. Based on prior precedent, an 80% acceptability rate was used as the minimum requirement for perceived air quality.

RESULTS

Results of measurements from 13 stores

Table 1 provides, in summary, the size and measured air exchange rates (AERs) in the 13 buildings, along with maximum outdoor air PM2.5 and PM10 levels from nearby locations, as reported by the California Air Resources Board (2012b).The Table includes air exchange rates for the three conditions of the intervention study in the big box store, which will be described below in the Results section.

Table 1 Description of 13 retail study buildings (includes three ventilation conditions for store BB)

Retail store	Description/Location	Sales floor area (m^2)	Indoor store height (m)	Measured Air Exchange Rates (1/h)	Annual state maximum (PM2.5/PM10)
G01*	Grocery, Berkeley CA	3270	8	0.75	12.8 / 22.4
G02*	Grocery, Walnut Creek CA	1839	7	1.45	9.4/24.1
G03*	Grocery, Tarzana CA	3307	10	0.77	16.4/38.9
F01	Furniture, San Francisco CA	641	4	1.12	11.6/21.9
F02	Furniture, Oakland CA	1533	6	2.38	12.8 / 22.4
F03	Furniture, Berkeley CA	678	4	0.39	12.8 / 22.4
F04*	Furniture, Fremont CA	6039	8	0.68	12.8 / 22.4
F05	Furniture, Long Beach CA	790	4	1.16	16.4/38.9
A01	Apparel, Oakland CA	120	3	2.32	12.8 / 22.4
A02	Apparel, Oakland CA	80	3	2.22	12.8 / 22.4
A03*	Apparel, San Mateo CA	1189	9	0.52	10.5/19.6
A04*	Apparel, Long Beach CA	1143	5	0.54	16.4/38.9
BB Baseline	Big Box retail store, Davis CA	10219	4	0.43	12.5/33.4
BB Low*	Big Box retail store, Davis CA	10219	4	0.24	12.5/33.4
BB Med.*	Big Box retail store, Davis CA	10219	4	0.69	12.5/33.4
BB High*	Big Box retail store, Davis CA	10219	4	1.51	12.5/33.4

*Store was surveyed while mechanical ventilation was in operation; others had natural ventilation only.

<u>VOCs and aldehydes – observed indoor concentrations vs. RELs</u>

Table 2 lists the measured ranges of concentrations of several CoC from the thirteen study buildings, compared to appropriate RELs. Note that two different RELs were employed for formaldehyde – the 9 $\mu g\ m^{-3}$ chronic REL from OEHHA that is exceeded in a substantial fraction of buildings and sometimes exceeded in outdoor air and the higher 16 $\mu g\ m^{-3}$ chronic

REL from NIOSH. Where available, reference outdoor concentrations were based on the 90th percentile of the last 4 years of outdoor measured state maximum concentration data (of 2011 to 2007) (ARB 2012). Alternatively, where no state-wide reference data was identified, reported outdoor concentration data was used (Bennett 2011: table 45 SMCB: Distribution of Outdoor Concentrations of VOCs Across All Buildings [95thpercentile]). For the IAQP calculations, reference outdoor data were considered preferable to the measured outdoor data; in most cases reference outdoor concentrations exceeded the measured outdoor concentrations, leading to higher (more conservative) IAQP-based VRs.

Table 2 Summary of indoor concentrations of key CoCs and reference levels

	Chronic Guidelines (μg/m^3)	**Indoor concentrations (μg/m^3) (average [Min-Max])**	**Outdoor ref. concentration (μg/m^3)**
Formaldehyde	9 (OEHHA), 19.6 (NIOSH)	19.4 [4.7-58.1]	5.8#
Acetaldehyde	9 (EPA)	13.9 [2.7-34.8]	3.3#
Octanal	2.1 (Odor)	2.3 [0.2-11.9]	0.81*
Acrolein	0.02 (EPA)	8.4 [0.5-43.9]	2.9#
Hexanal	32.4 (Odor)	14.7 [0.7-58.4]	1.11*

Source:* (Bennett, et al. 2011: Table 45), #ARB 2012

Calculation of IAQP-based VRs for 13 stores

IAQP-based minimum VRs were calculated for all CoCs; Table 3 through Table 5 give the IAQP-based minimum VRs for the top four (VOC or aldehyde) contaminants in each store with concentrations exceeding, or closest to, the applicable RELs. The principal contaminant of concern, which determined the highest IAQP VR, is identified in red. Contaminant concentration data represent the average of multiple measurements collected over one or more days, with the number of measurement days given for each store (n). Where multiple days of measurements were taken, results are also given (in brackets) for each day (if two days of measurements), or the range of measured values (more than two days). For the four key contaminants of concern, a calculation was also made of the percentage reduction in indoor sources of contaminants necessary to limit indoor concentrations to the RELs if Title-24 VRs were applied in each store. Table 6 shows the same information for the Big Box store, but considered only the three contaminants exceeding or closest to the applicable RELs. For the intervention study, the IAQP-based VR was calculated using outdoor contaminant concentration data measured during the baseline characterization. Table 7 gives IAQP calculation results using measured outdoor concentrations. These results were used as the basis for the applied IAQP-based ventilation rate. See Appendix A2 for detailed calculation methods.

Table 3Summary of IAQP-based VR calculation results for grocery stores

Store ID (measured ACH) [Title 24 ACH] (N[o] of days)	Contaminant	Average Outdoor Concentration [$\mu g/m^3$] (daily values)	Average Indoor Concentration [$\mu g/m^3$] (daily values)	Average emission rate ($\mu g/h{\bullet}m^2$)	IAQP VR ACH[1/h]/ [$l/s{\bullet}m^2$]	IAQP source emission % reduction at Title 24 VR
Store GO1 (0.75) [2.1] (n=2)	Acetaldehyde[^]	5.2 (2.8,7.5)	27.5 (28.8,26.1)	1.3E+02	2.9/6.2^	29%
	Formaldehyde[+&]	5.5 (3.0,8.1)	9.9 (9.6,10.3)	2.50E+01	1.0/2.2[+] 0.2/0.5[&]	NA[b+] NA[b&]
	Octanal*	0.0 (0.0,0.0)	1.7 (1.5,2.0)	1.00E+01	1.0/2.2*	NA[b]
	Acrolein[^]	13.0 (15.2,10.7)	22.1 (31.8,12.4)	5.14E+01	NA[a]	NA[a]
Store GO2 (1.45) [1.83] (n=2)	Octanal*	0.1 (0.3,0.0)	5.4 (5.9,5.0)	5.1E+01	6.0/11.1*	69%
	Acetaldehyde[^]	2.0 (1.7,2.3)	18.1 (15.5,20.7)	1.6E+02	4.1/7.6^	55%
	Formaldehyde[+&]	2.5 (1.8,3.3)	5.2 (5.2,5.3)	2.63E+01	1.2/2.3+ 0.3/0.5[&]	NA[b+] NA[b&]
	Acrolein[^]	4.0 (7.4,0.5)	5.7 (6.3,5.1)	1.67E+01	NA[a]	NA[a]
Store GO3 (0.77) [2.83] (n=1)	Acetaldehyde[^]	4.3	26.5	5.2E+01	3.0/2.5^	5%
	Formaldehyde[+&]	6.3	18.2	2.8E+01	2.9/2.4+ 0.7/0.6[&]	1 %+ NA[b&]
	Octanal*	0.1	0.2	3.7E-01	0.1/0.1*	NA[b]
	Acrolein[^]	1.2	11.0	2.3E+01	NA[a]	NA[a]

Note: n = Number of days of measurements;[^] Calculations based on EPA REL; [+] Calculations based on OEHHA REL; [&]Calculation based on NIOSH REL; * Calculations based on Odor/Pungency Threshold Value 2.1 $\mu g/m^3$;[$] Calculations based on Odor/Pungency Threshold Value 32.4$\mu g/m^3$; [a] Outdoor concentration exceeds REL; [b] Indoor concentration does not exceed REL, #Outdoor concentration exceeds indoor concentration

Table 4 Summary of IAQP-based VR calculation results for furniture stores

Store ID (measured ACH) [Title 24 ACH] (N[o] of days)	Contaminant	Average Outdoor Concentration [$\mu g/m^3$] (daily values)	Average Indoor Concentration [$\mu g/m^3$] (daily values)	Average emission rate ($\mu g/h \bullet m^2$)	IAQP VR ACH[1/h]/ [$l/s \bullet m^2$]	IAQP source emission % reduction at Title 24 VR
Store FO1 (1.1) [0.38] (n=2)	Formaldehyde[+&]	1.7 (1.4,2.0)	22.6 (21.2,23.9)	1.56E+02	7.3/13.7[+] 1.7/3.1[&]	95%[+] 78%[&]
	Acetaldehyde[^]	2.1 (1.9,2.2)	5.2 (4.5,5.9)	2.3E+01	0.6/1.1 ^	78%
	Octanal*	0.0 (0.0,0.0)	2.1 (2.1,2.1)	1.6E+01	1.8/3.4 *	79%
	Hexanal[$]	0.1 (0.0,0.2)	11.5 (10.7,12.9)	8.73E+01	0.4/0.8[$]	NA[a]
Store FO2 (2.38) [1.66] (n=1)	Formaldehyde[+&]	4.1	16.2	8.8E+01	9.1/7.7[+] 2.1/1.8[&]	82%[+] 20%[&]
	Octanal*	0.0	0.8	6.1E+00	1.6/1.3*	NA[b]
	Acetaldehyde[^]	2.5	4.3	1.36E+01	0.8/0.7^	NA[b]
	Acrolein[^]	0.2	1.4	9.0E+00	NA[a]	NA[a]
Store FO3 (0.39) [1] (n=1)	Formaldehyde[+&]	2.3	25.5	2.7E+01	2.8/2.4[+] 0.6/0.5[&]	65%[+] NA[b&]
	Octanal*	0.0	2.5	2.9E+00	0.7/0.6*	NA[b]
	Acetaldehyde[^]	2.6	8.7	7.07E+00	0.4/0.3^	NA[b]
	Acrolein[^]	0.1	0.5	4.7E-01	NA[a]	NA[a]
Store FO4 (0.68) [2.05] (n=1)	Formaldehyde[+&]	3.0	24.7	1.1E+02	4.6/9.7[+] 1.1/2.2[&]	56%[+] NA[b&]
	Octanal*	0.0	3.8	2.0E+01	2.0/4.2*	NA[b]*
	Acetaldehyde[^]	2.1	18.6	84.05	2.0/4.1^	NA[b]^
	Hexanal[$]	0.3	58.4	3.0E+02	1.3/2.6$	NA[b]
Store FO5 (1.16) [0.98] (n=1)	Formaldehyde[+&]	2.7	29.0	1.1E+02	9.6/9.6[+] 2.2/2.2[&]	90%[+] 55%[&]
	Octanal*	ND	1.7	7.0E+00	1.5/1.5*	35%*
	Acetaldehyde[^]	2.3	5.9	1.55E+01	0.8/0.8^	NA[b]
	Hexanal[$]	0.4	14.1	5.7E+01	0.5/0.5[$]	NA[b]

Table 5 Summary of IAQP-based VR calculation results for a subset of apparel stores

Store ID (measured ACH) [Title 24 ACH] (N° of days)	Contaminant	Average Outdoor Concentration [µg/m³] (daily values)	Average Indoor Concentration [µg/m³] (daily values)	Average emission rate (µg/h•m²)	IAQP VR ACH[1/h]/ [l/s•m²]	IAQP source emission % reduction at Title 24 VR
Store AO1 (2.32) [0.83] (n=1)	Formaldehyde[+&]	5.4	23.7	2.2E+02	22.2/18.9[+] 5.1/4.3[&]	94%[+] 73%[&]
	Acetaldehyde[^]	8.0	6.3	NA[#]	NA[#]	NA[#]
	Octanal*	0.1	0.2	1.9E+00	0.5/0.4*	NA[b]
	Acrolein[^a]	0.1	3.0	3.4E+01	NA[a]	NA[a]
Store AO2 (2.22) [0.92] (n=1)	Formaldehyde[+&]	3.6	58.1	3.5E+02	33.0/30.8[+] 7.6/7.1[&]	97%[+] 88%[&]
	Acetaldehyde[^]	3.0	8.3	3.5E+01	1.8/1.7^	49%^
	Octanal*	0.1	1.0	6.4E+00	1.5/1.4*	38%^
	Hexanal[$]	0.2	7.6	4.8E+01	0.5/0.4[$]	NA[b]
Store AO3 (0.52) [2.54] (n=1)	Formaldehyde[+&]	1.7	8.1	3.1E+01	1.0/2.7[+] 0.2/0.6[&]	NA[b+] NA[b&]
	Acetaldehyde[^]	2.2	4.9	1.3E+01	0.2/0.6^	NA[b]
	Octanal*	ND	0.5	2.5E+00	0.2/0.5*	NA[b]
	Hexanal[$]	ND	4.8	2.3E+01	0.1/0.2[$]	NA[b]
Store A04 (0.54) [1.45] (n=1)	Formaldehyde[+&]	2.7	11.8	2.6E+01	1.5/2.3[+] 0.4/0.5[&]	6%[+] NA[b&]
	Octanal*	ND	3.0	8.7E+00	1.3/1.9*	NA[b]
	Acetaldehyde[^]	2.4	13.7	3.23E+01	1.1/1.6^	NA[b]
	Hexanal[$]	ND	24.0	6.8E+01	0.4/0.6[$]	NA[b]

Table 6 Big Box Retail Store: Summary of IAQP-based VR calculation results for big box store using reference outdoor concentrations.

Store ID (measured ACH) [Title 24 ACH] (N° of days)	Contaminant	Average Outdoor Concentration [µg/m³] (daily values)	Average Indoor Concentration [µg/m³] (daily values)	Average emission rate (µg/h•m²)	IAQP VR ACH[1/h]/ [l/s•m²]	IAQP source emission % reduction at Title 24 VR
Store BB (0.43) [1.05] (n=5)	Formaldehyde[+&]	1.9 (0.7-4.0)	25.6 (23.6-27.2)	3.96E+01	2.9/3.8[+] 0.7/0.9[&]	NA[b+] NA[b&]
	Acetaldehyde[^]	2.0 (1.5-2.8)	8.8 (8.1-9.6)	1.15E+01	0.5/0.6^	NA[b]
	Octanal*	0.0 (0.0-0.0)	1.5 (0.9-3.9)	2.57E+00	0.5/0.6*	NA[b]

Table 7 Big Box Retail Store: Summary of IAQP-based VR calculation results for big box store using measured outdoor concentrations.

Store ID (measured ACH) [Title 24 ACH] (N° of days)	Contaminant	IAQP VR ACH[1/h]/ [l/s•m²]	IAQP source emission reduction at Title 24 VR
Store BB (0.43) [1.05] (n=5)	Formaldehyde[+&]	1.3/1.7[+] 0.5/0.7[&]	NA[b+] NA[b&]
	Octanal*	0.5/0.6*	NA[b]
	Acetaldehyde^	0.4/0.5^	NA[b]

For the three grocery stores, acetaldehyde and octanal defined the IAQP-based VRs. IAQP-VRs for the three grocery stores G01, G02 and G03, were 2.9, 6, and 3 ACH, respectively. These rates are significantly higher than both the current VRs and Title-24 prescribed minimum rates.

In all five furniture stores, formaldehyde was the dominant contaminant of concern based on the objective IAQP calculation. When the OEHHA REL is used, the minimum IAQP-based VRs all exceed both measured VRs and Title-24 rates. If the less stringent NIOSH standards were applied, IAQP-based rates still exceeded Title 24 rates, in the majority of stores.

Formaldehyde was again the dominant driver of the IAQP-based VRs in the apparel stores, with IAQP VRs exceeding current VRs or Title-24 VRs in stores A01 A02 and A04. By contrast, in store A03, IAQP-based VRs were significantly lower than both measured rates and rates prescribed by Title 24, indicating the store is potentially over-ventilated.

The IAQP calculation for the Big Box retail store identified formaldehyde as the principal driver of the IAQP VR, with all other measured contaminants below reference levels at the surveyed baseline ventilation rate. The IAQP VRs exceeded the existing VR but were slightly below the Title 24 VR.

<u>IAQP results for particles</u>

Indoor particle mass concentrations were compared against both 24 hour and chronic RELs in each of the thirteen stores. Figure 2 and Figure 3 give average indoor PM2.5 and PM10 concentrations in the thirteen retail stores. Based on results of mass balance calculations, indoor concentrations are differentiated by whether they originated from outdoor (Cin_o) or indoor sources (Cin_i), for the calculation method see Appendix A3.Several assumptions were made to perform this mass balance calculation, resulting in a significant level of uncertainty. In grocery store GO3, mass balance modeling indicated that the majority of indoor particles came from indoor sources. By contrast, the majority of particles in A01 and F01 originated from outdoors. For the Big Box retail store, this calculation was performed using data measured at each of the three study VRs, no particle mass monitoring was performed during the Big Box baseline study.

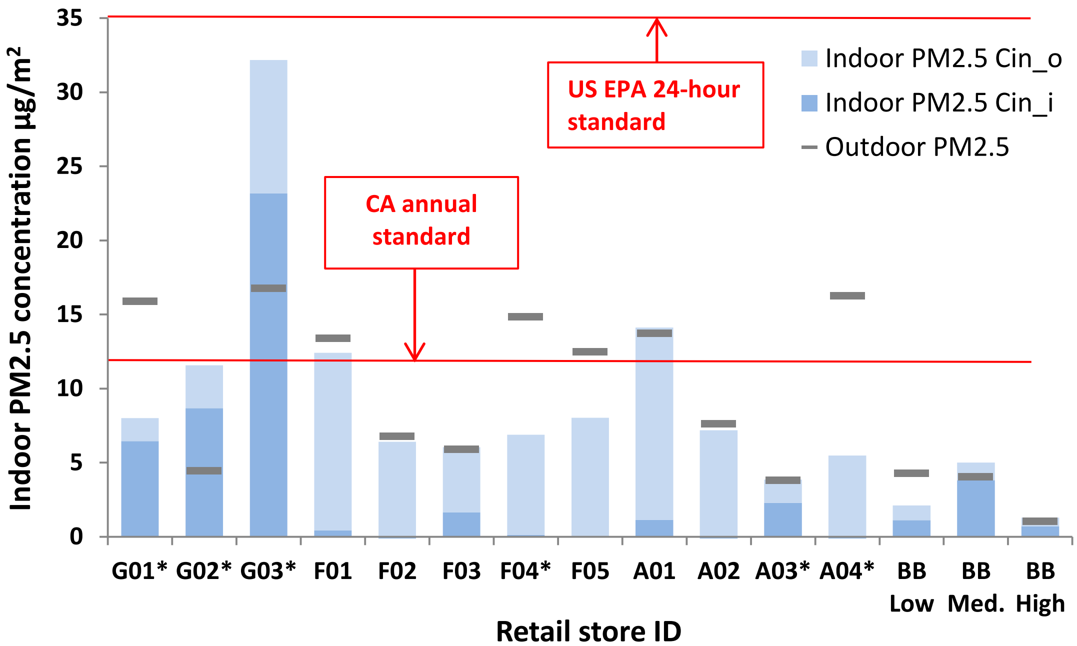

Figure 2 Estimated indoor concentration of PM2.5 by source

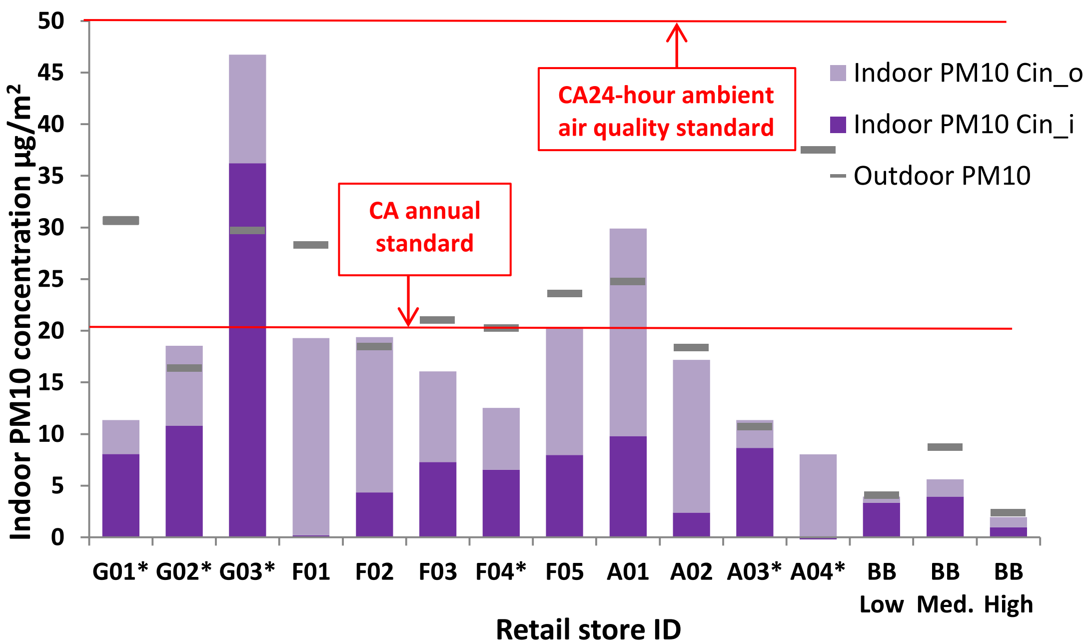

Figure 3 Estimated indoor concentration of PM10 by source

The estimated indoor particle emission rates are given in Figure 4.

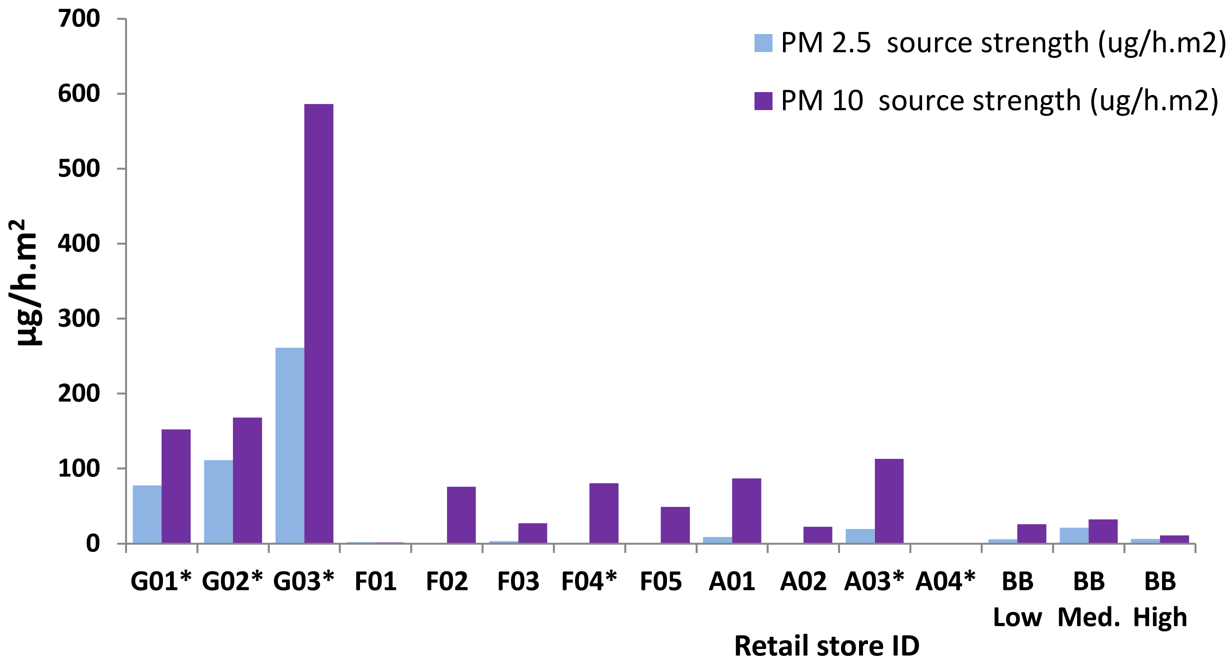

Figure 4 Estimated indoor particle emission rates

Mass balance models were used to predict the impact of a range of outdoor air VRs on indoor particle concentrations. Assumptions were made regarding the fraction of outdoor air entering the building through the mechanical systems (when present) or entering through windows or open doors (see Appendix A3). Four-year annual state maximum outdoor particle concentrations for each county were used in these models to represent outdoor concentrations at each of the thirteen study buildings. Outdoor particle concentrations vary significantly from day to day and by season, consequently, reference outdoor concentrations, being more representative of regional averages, were used in the IAQP calculations. Figure 5 to Figure 10give modeled indoor PM2.5 and PM10 concentrations as a function of VR ranging from zero to a maximum of (4.6 $l/s{\bullet}m^2$). Maximum VRs were dictated by reported typical measured supply air flow rates (see Appendix A3). When mechanical systems were present, the MERV rating of the HVAC system's particle filters is indicated in each plot legend. For reference, a California Title 24 prescribed VR of 0.2 cfm/ft^2 is equivalent to 1 $l/s{\bullet}m^2$.

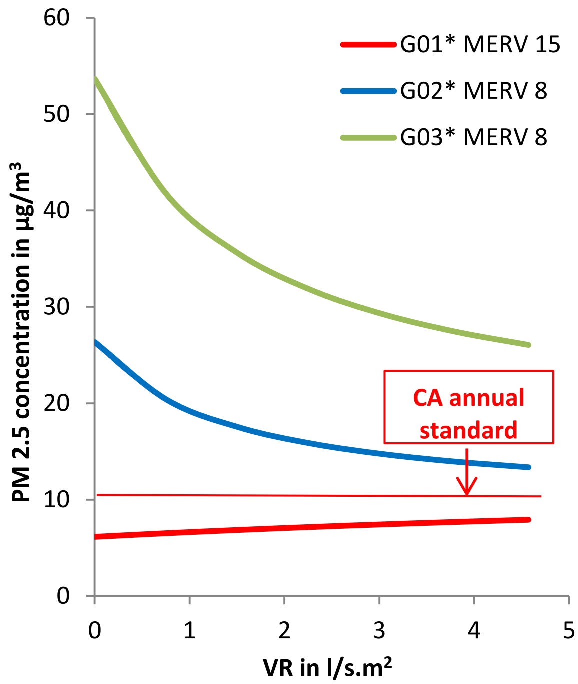

Figure 5 Measured and modeled PM 2.5 in grocery stores

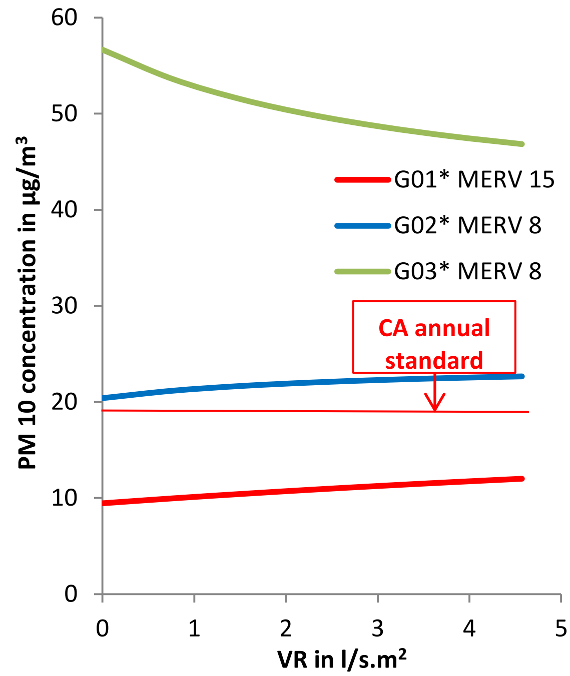

Figure 6 Measured and modeled PM 10 in grocery stores

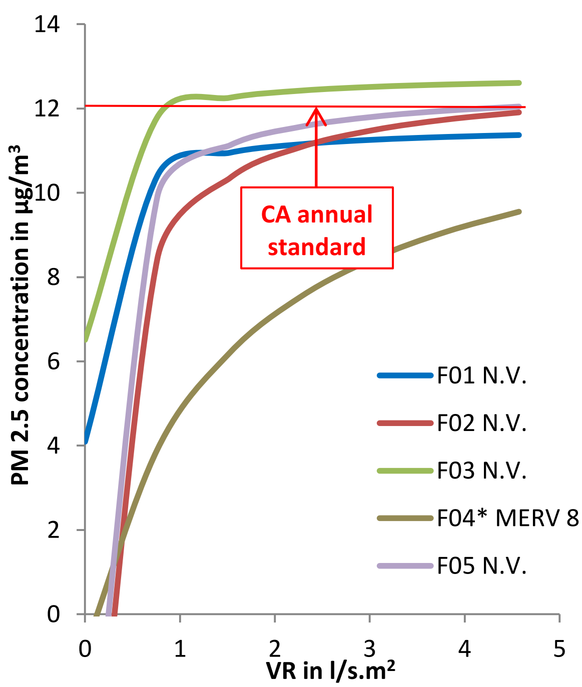

Figure 7 Measured and modeled PM 2.5 in furniture stores

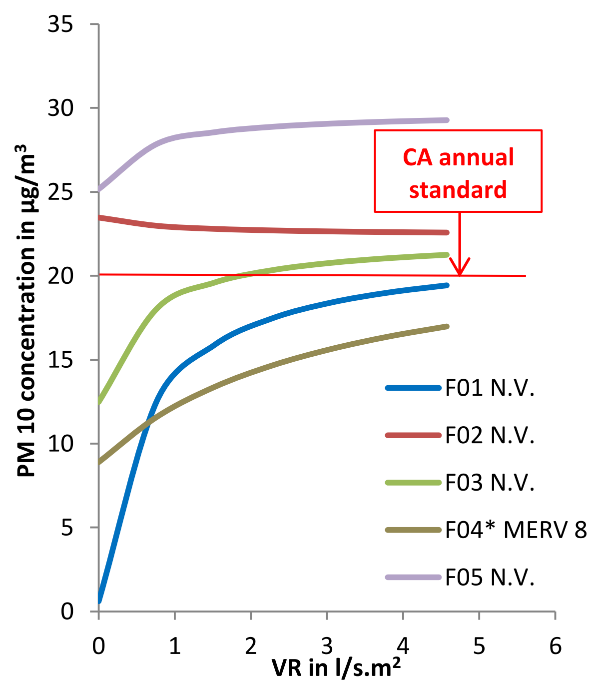

Figure 8 Measured and modeled PM 10 in furniture stores

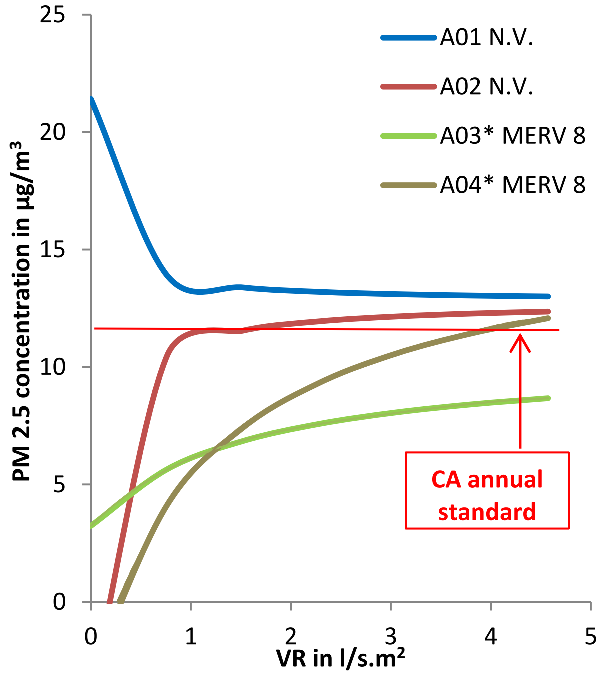

Figure 9 Measured and modeled PM 2.5 in apparel stores

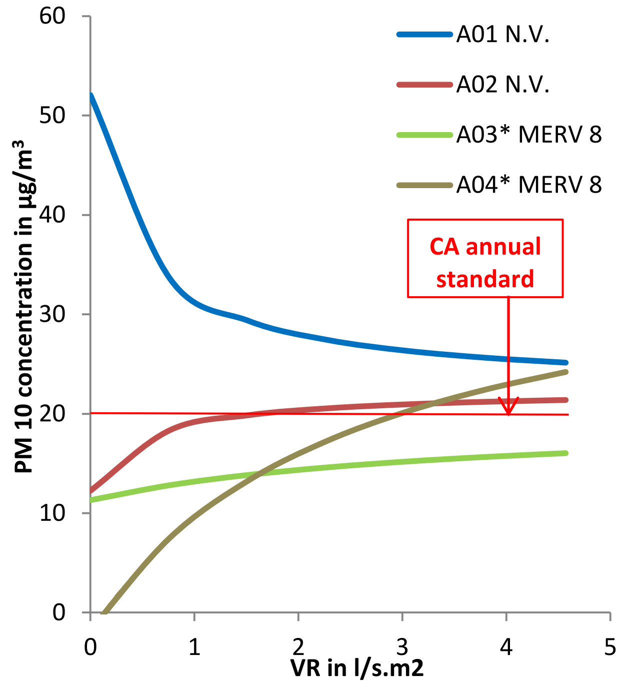

Figure 10 Measured and modeled PM 10 in apparel stores

The IAQP analysis for particles is summarized by Table 7. The majority of stores met current California RELs for PM2.5 and PM10. Based on the mass balance models, adjusting ventilation alone, it was possible to meet PM2.5 REL in G02, F02, F03, F05, and A02. PM10 guidelines in stores F01, F03, A02, and A04 could also be met through suitable adjustment of VRs. Of these four cases, the IAQP-based VR was higher than the measured VR in three buildings (F01, F03 and A04) and lower in building (A02).

In the seven buildings with mechanical ventilation, a calculation was performed of the filtration efficiency required to limit indoor particle concentrations to CAEPA annual guidelines. For two of the seven mechanically ventilated buildings, indoor concentrations were so low that even with filter efficiencies of zero, indoor concentrations were still below RELs. By contrast, indoor concentrations in building G03 still exceeded guidelines with a modeled 100% efficient filtration. For this case, source control measures were modeled; 92% and 69% reductions in PM2.5 and PM10 emission rates, respectively, were required to lower their concentrations to below RELs.

Table 7 IAQP Calculation results for particles in thirteen retail stores

Retail store	IAQP ventilation rate (based on PM2.5) l/s•m^2	IAQP ventilation rate (based on PM10) l/s•m^2	Measured ventilation rate (l/s•m^2)	Minimum filtration efficiency for PM2.5, CA Title 24 VR	Minimum filtration efficiency for PM10, CA Title 24 VR	Approximate MERV rating Equivalent	Currently installed filter MERV rating
G01*	92.4$^\$$	81.8$^\$$	1.7	34%	20%	8	15
G02*	7.6	>100$^\#$	2.8	39%	28%	8	8
G03*	>100 $^\#$	>100$^\#$	2.1	121%$^\&$	142%$^\&$	>15	8
F01	>100 $^\#$	6.1	1.2	-	-	-	-
F02	5.1	<0$^\$$	4.0	-	-	-	-
F03	1.0	1.9	0.4	-	-	-	-
F04*	22.5$^\$$	14.2$^\$$	1.5	<0 $	<0$^\$$	1	8
F05	4.2	>100$^\#$	1.3	-	-	-	-
A01	>100$^\#$	>100$^\#$	2.0	-	-	-	-
A02	2.4	1.6	1.9	-	-	-	-
A03*	>100$^\#$	>100$^\#$	1.3	<0$^\$$	<0$^\$$	1	8
A04*	4.4$^\$$	3.0$^\$$	0.8	<0$^\$$	<0$^\$$	1	8
BB Low	27.8$^\$$	<0$^\$$	0.3	<0$^\$$	<0$^\$$	1	7
BB Med.	17.4$^\$$	<0$^\$$	0.9	<0$^\$$	<0$^\$$	1	7
BB High	27.4$^\$$	<0$^\$$	1.9	<0$^\$$	<0$^\$$	1	7

Notes: $^\$$ modeled Cin < REL over range of reasonable VRs; $^\#$ IAQP VR exceeds range of reasonably attainable VRs; $^\&$ required filtration efficiency exceeds 100%; * modeled Cin < REL over range of filtration efficiencies

Intervention Study

Indoor concentrations of CoC were measured throughout each of the three intervention VRs. Indoor concentrations of both PM2.5 and PM10 were found to be significantly lower than maximum CA annual standards shown in Figure 2 and Figure 3 respectively. Increased ventilation was found to have no significant impact on indoor particle concentrations and so would not be an effective means of controlling indoor particles. Results in Table 7 give IAQP-based VRs and minimum required filtration efficiencies necessary to meet CA annual standards, given indoor particle emission rates found at the three study VRs. Modeling changes in filtration efficiency indicated that even with effectively zero filtration, particle levels would still have been below CA guidelines.

Results from the VOC IAQP VR calculations performed using the Big Box observational field study data, found that formaldehyde, acetaldehyde and octanal were the three CoCs that were closest to, or exceeded CRELs. Results of the IAQP calculation in Table 7 predicted that formaldehyde was the most significant driver of an IAQP-based VR, and that a VR of 1.3 ACH would be sufficient to lower indoor concentrations of formaldehyde to meet the most stringent reference guideline, OEHHA’s CREL. The actual measured VR during the study week with the “high” IAQP-based VR was found to be 1.5 ACH (reference Table 1). At this rate, all CoCs were controlled below RELs (within margins of error), including formaldehyde. Figure 11, Figure 12 and Figure 13 give indoor concentration of formaldehyde, acetaldehyde and octanal at the three intervention VRs, and corresponding guideline RELs.

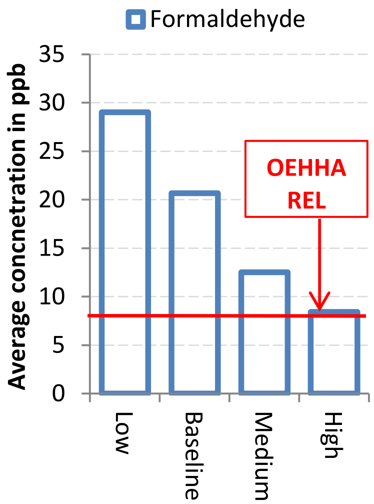

Figure 11 Formaldehyde concentrations in ppb

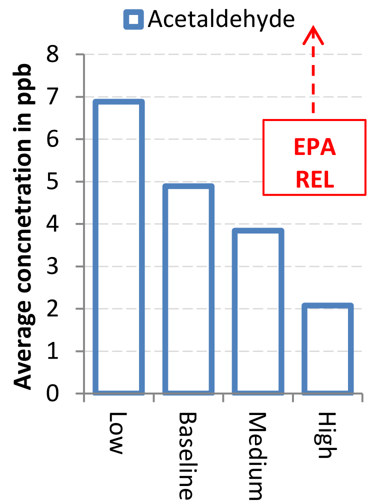

Figure 12 Acetaldehyde concentrations in ppb

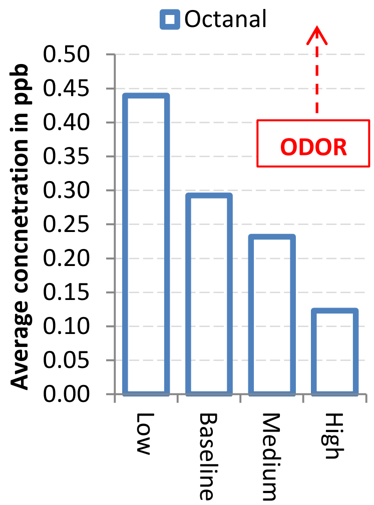

Figure 13 Octanal concentrations in ppb

A companion report Dutton et al (2013) provides further details of the indoor and outdoor concentrations, and emission rates of the CoC, at all three intervention VRs.

Results from Surveys

Survey participant demographics

The majority (62%) of respondents were between the ages of 18 and 22, 98% identified themselves as being non-smokers, 34% had previously been diagnosed with allergies, and 16% had previously been diagnosed with asthma.

Table 8 gives the gender ratios for each study VR. The male-to-female ratio was significantly different than our preferred 50-50 balance. A full breakdown of age, demographic, and health factors (including gender, employment status, asthma, and allergy status) can be found in Appendix B, Figure A17.

Table 8: Gender break down by study ventilation rate

	Ventilation Rate		
Gender	**Low**	**Medium**	**High**
Male	29.3%	38.6%	56.8%
Female	70.7%	61.4%	43.2%

Subject response analysis

Table 9 summarizes the binary response on acceptability for each study VR, weighted by gender ratio, and presented separately for initial unadapted, average unadapted, and average adapted responses. In all cases, the targeted minimum acceptability rating of 80% was exceeded; i.e., more than 80% of both males and females rated the IAQ as acceptable. The average binary responses for unadapted subjects (Table 9) were 90.3%, 95.5% and 98.9% acceptability at low, medium, and high ventilation rates, respectively.

Table 9 Dichotomized acceptability of indoor air quality for unadapted and adapted responses.

Survey responses	Low VR (0.24 ACH)	Medium VR (0.69 ACH)	High VR (1.51 ACH)
First unadapted	86.8% (96%M, 83%F)	100% (100%M, 100%F)	100% (100%M, 100%F)
Average unadapted	90.3% (96%M, 88%F)	95.5% (93%M, 97%F)	98.9% (100%M, 98%F)
Average adapted	96.0% (96%M, 96%F)	92.2% (91%M, 93%F)	95.3% (97%M, 94%F)

Figure 14 gives the subjects' continuous responses on a scale from -1.0 to 1.0, broken down by study period VR. Distributions appeared bimodal or possibly tri-modal, with large irregular peaks.

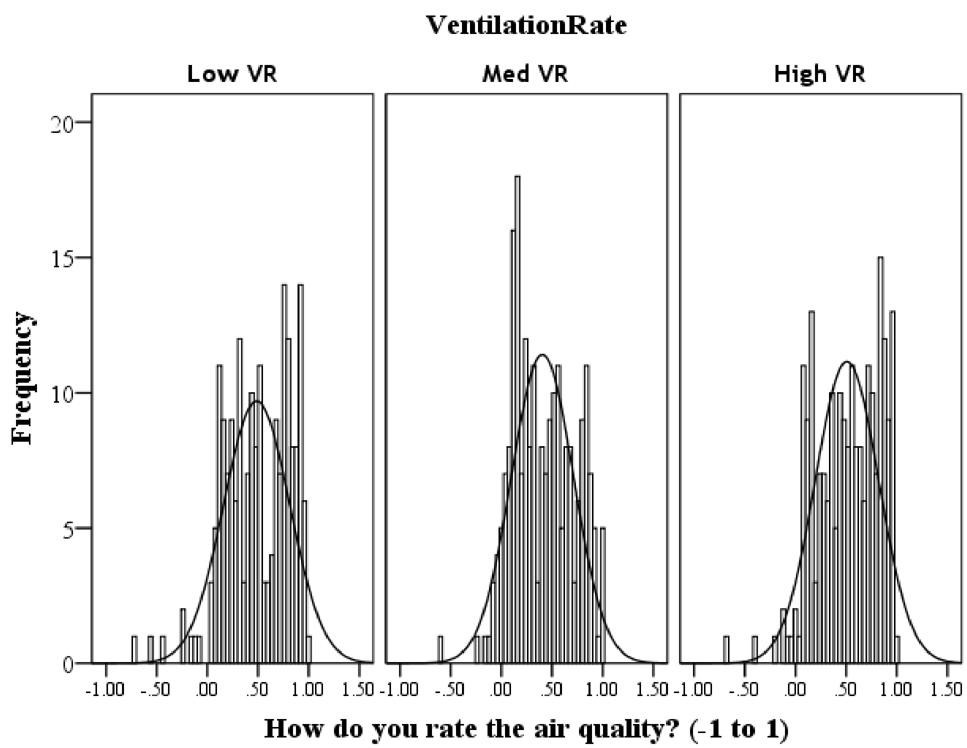

Figure 14: Distribution of air quality rating paneled according to VR, from clearly unacceptable (-1) to clearly acceptable (1), combining adapted and un- adapted responses at stations 1-5.

The mean air quality responses for all three VRs combined was marginally higher for unadapted responses (0.49 [sd =0.28, min=-0.22, max=1]), than for adapted responses (0.45 [sd =0.24, min=-0.15, max=0.94]). A paired T-test indicated that the mean adapted rated air quality reported was significantly lower (p=0.02) than the mean unadapted rated air quality. A non-parametric Wilcoxon signed-rank test showed similar results. Mean reported values of acceptability are given in Table 10.

Table 10 Average responses

Survey responses	Ventilation Rate Low mean (sd)	Medium mean (sd)	High mean (sd)
First unadapted	0.50 (0.31)	0.50 (0.28)	0.55 (0.25)
Average unadapted	0.48 (0.35)	0.45 (0.29)	0.55 (0.28)
Average adapted	0.48 (0.33).	0.38 (0.31)	0.49 (0.33)

There is a suggestion of a positive trend in acceptability as VRs increased from low to high, changing from 0.50 to 0.55 and 0.48 to 0.55 in the first unadapted and average unadapted responses, respectively. An F-Test based on the one-way ANOVA showed that the mean levels of acceptability for the three VRs were not significantly different for adapted responses (p= 0.08), but were significantly different for unadapted responses ($p < 0.0001$), despite the lack of a monotonic relationship with VRs.

In terms of differences between unadapted and adapted responses at each VR, a similar pattern was evident for the proportion of binary and continuous acceptability responses. Adapted acceptability was slightly lower than unadapted acceptability, but only at high and medium VRs.

Male respondents represented 42% of the total. There was no statistically significant difference between the mean air quality reported for adapted responses of men and women (0.0 for men and 0.0 for women, respectively; p=0.24). There was also no statistically significant difference between the mean reported unadapted responses of men and women (0.0 for men and 0.0 for women, respectively; p=0.52). The non-parametric Wilcoxon rank-sum test showed similar non significant results.

Respondents who had been diagnosed with asthma represented 17% of the total. There was no statistically significant difference between mean air quality reported by asthmatics and non-asthmatics, either for adapted responses (0.0 for asthmatics and 0.0 for non-asthmatics, respectively; p=0.45) or for unadapted responses (0.0 for asthmatics and 0.0 for non asthmatics, respectively; p=0.71). The non-parametric Wilcoxon rank-sum test showed similarly non-significant results.

The average number of respondents who had been diagnosed with allergies represented 44% of the total sample. There was no statistically significant difference between mean air quality reported by allergic and non-allergic people, either for adapted responses (0.0 for allergic and 0.0 for non-allergic, respectively; p=0.065) or for unadapted responses (0.0 and 0.0, respectively; p=0.41). The non-parametric Wilcox on rank-sum test showed similarly non-significant results.

Average temperature ranged between 20 and 23°C. There was a non-significant -0.09 correlation between temperature and reported mean adapted air quality response (similarly -0.03 non-significant Spearman's rho (non-parametric)). There was a non-significant -0.13 correlation between temperature and reported mean unadapted air quality response (similarly -0.09 non-significant Spearman's rho (non-parametric)). Average relative humidity ranged from 22 to 41%. There was a non-significant 0.12 correlation between relative humidity and reported mean adapted air quality response. The non-parametric Spearman's rho correlation was 0.18 and significant with p-value = .046. There was a non-significant -0.02 correlation between relative humidity and reported mean unadapted air quality response (similarly 0.05 non-significant Spearman's rho (non-parametric).

Figure 15 presents the subjects' responses to surveys 1-5, ordered by the time at which each survey was taken, for each study VR. Outliers are identified by Subject ID-Station number-Order sequence. No apparent pattern is suggested regarding trends across the station numbers and across VR conditions.

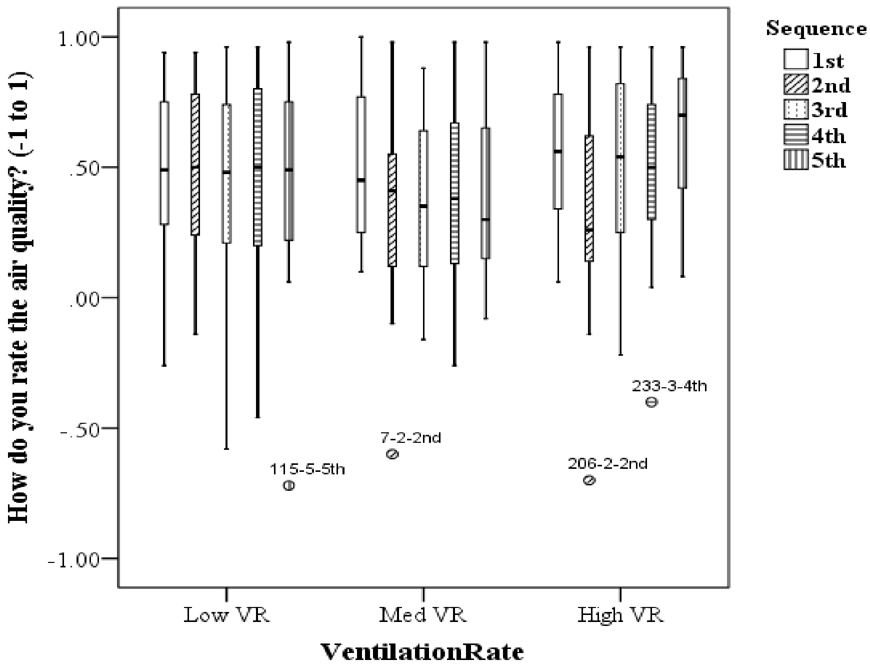

Figure 15 Distribution of responses to "How do you rate air quality?"

DISCUSSION

Key findings

Measured indoor particle counts were found to exceed California's REL for PM2.5 in three of 13 stores. Measured PM10 concentrations exceeded California's REL in four of13 buildings. The three grocery stores had significant sources of PM2.5, sources attributed anecdotally to in-store food preparation. Because outdoor particle concentrations were often found to exceed indoor concentrations, no reasonable alternative modeled VR could have been used to meet RELs for the majority of retail stores surveyed. Where the principal source of particulate contaminants was outdoors, increased filtration efficiency was, based on models, predicted to significantly lower indoor particle concentrations. Improved filtration was also predicted to control indoor particle contamination from indoor sources to a limited extent. For scenarios with high indoor particle emission rates, increased filtration alone was not sufficient to maintain concentrations below

RELs without also increasing air recirculation rates. However, increasing either mechanical VRs or air recirculation rates has an associated undesirable energy cost. For building G03, increased filtration or ventilation alone was not sufficient; the proposed IAQP-compliant strategy for this building was a combination of increased filtration and measures to control particle sources. For the other twelve buildings, the MERV rating of the filter currently in use was sufficient to meet RELs.

There were no identified significant indoor sources of either ozone or carbon monoxide. Sources of these contaminants were found to originate from outdoor air, and therefore increased ventilation could not be used, in these cases, to lower indoor concentrations. Therefore, it should be taken into consideration that any increased ventilation that would be applied, as a result of applying the IAQP to remove indoor source contaminants, would likely increase the ingress of outdoor sourced contaminants.

Measured indoor VOC and aldehyde concentrations were found to exceed RELs for at least one contaminant, in all surveyed stores. Mass balance models were used to simulate indoor contaminant concentrations in these stores, assuming application of current Title 24 ventilation standards. At Title-24 ventilation rates, only two of the modeled stores (A03 and the BB store) were shown to maintain all indoor CoC concentrations below RELs. It could be argued, therefore, that for the majority of buildings, neither the surveyed VRs nor prescribed Title-24 VRs were sufficient to protect occupants from exposure to CoC concentrations that exceed current RELs. Emission rates for VOC and aldehyde CoCs were calculated and used to perform IAQP calculations for each store. Using the OEHHA REL, formaldehyde was the dominant driver of the IAQP-based ventilation rate in all stores with the exception of the three grocery stores. It should be noted however that there are significant differences in formaldehyde RELs published by relevant authorities, ranging from the stringent 9µg/m^3 (OEHHA) to 98 µg/m^3 (World Health Organization [WHO] (2010)). Applying the NIOSH REL, formaldehyde was still the most significant driver in the majority of stores, however if the World Health Organization REL is applied then acetaldehyde and octanal become the dominant drivers of IAQP ventilation rates.

IAQP-based VRs exceeded Title 24-prescribedVRs in all stores exceptA03 and the BB store. In 62% of surveyed stores, the IAQP-based VRs were found to be above 3 ACH, and in 54% of cases IAQP-based VRs exceeded 5ACH. In these cases, using ventilation alone to manage indoor contaminants would likely be prohibitively expensive, in terms of both the increase in ongoing energy use, and any increase in the ventilation system size required to provide these higher VRs. Under these circumstances, source control or application of air cleaning systems for VOCs are the alternative strategies to consider. However, source control is complex because of the large number and changing nature of sources and it is not clear that air cleaning technologies for VOCs are sufficiently effective and affordable for widespread use in buildings (Fisk 2007).

The intervention study in the BB store found that for the majority of our VOC CoCs, increased ventilation was effective at lowering steady state indoor concentrations. Increased ventilation did not result in lower indoor concentrations of contaminants that originated from outside, including ozone and particles. At the IAQP-based ventilation rate indoor contaminant concentrations of all CoC's were maintained below relevant RELs.

In the subjective assessment of perceived air quality performed in the BigBox store, satisfaction with air quality exceeded the target of 80% at all VRs for both men and women. There was a non-significant increase in perceived air quality with increasing ventilation rates as subjects first entered the store. Unadapted subjects (Table 9) reported 90.3%, 95.5% and 98.9% acceptability at our three study ventilation rates: a baseline low rate, a prescribed Title24-based rate, and our IAQP-based rate. For adapted responses, there was no clear relationship of perceived air quality with VRs. T-test results indicated that for unadapted responses, there was no significant difference in responses between women and men, between asthmatics and non-asthmatics, or between people with and without diagnosed allergies. Comparing mean responses from unadapted (0.49) and adapted responses (0.45) indicated that perceived air quality decreased marginally as subjects remained within the store more than a few minutes and also moved deeper into the store. This contradicts the expected result, if odor was the driver for perceived air quality, that subjects would report higher perceived air quality as they adapted to the store environment over time. This could be interpreted as evidence that local variations in odor act to counter any general adaption to the store environment. This has potentially broader implications for ventilation standards that rely on perceived IAQ, using adapted subjects.

Study Limitations

This study alone is insufficient to form the basis for general recommendations for minimum commercial VRs in retail stores. However, the results of this study, together with results from work by Chan (2012) and ongoing evaluations of chronic health effects, as a function of VRs, will provide a clearer picture of the minimum VRs required to limit contaminant concentrations to acceptable levels for retail stores.

Perceived IAQ surveys were performed as part of our IAQP assessment in a single Big Box retail store. Surveys in more buildings would be preferable, but were not possible due to cost constraints. Therefore we only have data from a single store to determine how the subjective portion of the IAQP affects required minimum VRs.

The reliance only on simulated shoppers to evaluate satisfaction with IAQ is a limitation. It would have been preferable to also evaluate the satisfaction with IAQ expressed by actual shoppers and store employees. Interference with shoppers or store employees had been ruled out by the owner of the Big Box retail store.

The subjects in our survey of perceived air quality did not include potentially sensitive populations such as children, the elderly, and people who identify themselves as being particularly sensitive to airborne contaminants. We had three main reasons for excluding the above groups. Firstly, we do not have a basis for clear identification of sensitive subpopulations for the outcome of perceived air quality (e.g., Are the elderly more or less sensitive?).Secondly, the added cost of recruiting a sufficiently large number of subjects who fit narrow selection criteria (e.g., chemically sensitive individuals) was prohibitive. Thirdly, obtaining human subject’s approval to survey children or subjects with serious preexisting diseases would have been prohibitively costly and uncertain. Subjects recruited in this study were likely to be young, healthy, adults, but often with allergies or asthma. Our study plan called for each week’s subjects to include 50% women and 50% men. However, our requirement to recruit enough subjects for each study outweighed our preference to balance gender, resulting in a gender imbalance.

Implications of applying IAQP

The key change in approach with the IAQP, relative to the VRP, is to consider outdoor air ventilation as just one of several possible tools for achieving adequate IAQ. This would be an important step towards reducing energy use in buildings, while maintaining or improving IAQ. Ventilation rate standards that are linked to achieving specified levels of indoor pollutants and acceptability, rather than being prescribed without explicit consideration of air quality, could better provide healthy indoor environments. Such standards could also reward designers and owners who control indoor pollutants, by allowing lower energy costs from reduced outdoor air ventilation. In theory, this is a win-win strategy. In practice however, if one applies stringent RELs, applying the IAQP can have the effect of increasing energy use, unless effective alternatives to increased ventilation are also considered. For the majority of our example cases, using ventilation alone to control indoor concentrations of contaminants resulted in IAQP VRs that were significantly higher than the minimum VRs specified in ASHRAE VR procedure or in Title 24. For these examples, other measures to control sources or concentrations of indoor contaminants would have been necessary to realize energy savings whilst still meeting RELs.

In buildings with already low indoor contaminant source strengths, application of the IAQP to lower VRs has immediate potential to save energy, without requiring additional control methods. Any potential energy savings realized by applying the IAQP to lower VRs would be further increased if indoor contaminant concentrations were lowered via effective use of indoor pollutant source control measures or gas phase air cleaning technologies. No assessment can be made of the size of this opportunity with existing data, although we suspect the potential energy savings could be substantial.

A complementary effort (Parthasarathy 2012b) is estimating the chronic health risks for a range of VRs in retail and other types of buildings. These studies are parts of a larger research effort designed to provide a stronger scientific basis for ventilation standards that balance energy efficiency with provision of acceptable indoor environments for occupants.

Improved specifications for an IAQP

At present, the users of the ASHRAE IAQP have complete flexibility to select “critical contaminants” and RELs. Many users will not have the necessary expertise to select the contaminants most relevant to occupant’s health. Also, there are no constraints that prevent an IAQP user from making selections that provide the answer they desire. It is therefore recommended that future versions of an IAQP, including any version developed for inclusion in Title 24, include lists of critical contaminants to be considered and appropriate RELs to be utilized. One such source for identifying those critical contaminants is Srinandini, et al. (2012), with the caveat that in buildings with unusual pollutant sources, the user would need to consider the additional relevant critical contaminants.

ASHRAE’s IAQP requires that the user select a minimum level of acceptability for IAQ, interpreted as the minimum percentage of occupants satisfied with IAQ. The protocol also requires that “a subjective occupant evaluation conducted in the completed building determine the minimum outdoor airflow rates required to achieve the level of acceptability specified”. This subjective test of acceptability is widely considered impractical. Also, few IAQP users will have the expertise needed to implement the subjective test. If this requirement is maintained, specifications defining the subjective assessment method should be added. At a minimum, these specifications should include the number of subjects, the survey question, a basic description of the survey protocol, and the minimum level of acceptability. However, an IAQP that omitted or had a subjective evaluation that was more practical to apply would be preferable.

Equivalent IAQ Procedure (EIAQP)

ASHRAE's IAQP, if implemented with a specified set of suitable critical contaminants and stringent RELS, effectively establishes a higher bar for IAQ than the VR procedure. For example, many buildings applying the VR procedure now fail to maintain formaldehyde levels below stringent RELs for formaldehyde; however, if they applied the IAQP they would need to maintain concentrations of formaldehyde below the RELs. As an alternative to the current IAQP, it would be possible to develop an equivalent IAQ procedure (EIAQP) designed to give users more flexibility but still maintain indoor concentrations of CoC at or below the levels expected with the VR procedure. The EIAQP, like the standard VR procedure, would not, however, assure that levels of CoCs are maintained below RELs. A minimum rate of outdoor air supply per person and per unit floor area would be maintained, perhaps at 50% of the currently specified values in the VR procedure. A set of CoC would be specified. Users would be free to employ indoor pollutant source control measures and air cleaning techniques in conjunction with lower VRs, as long as they could demonstrate through measured data, and/or modeling based on data, that the indoor air concentrations of all CoC were maintained equal to or less than concentrations expected or previously measured with the VR procedure. For example, users of the EIAQP could decrease VRs by the full 50% allowed, which would (without countermeasures) double indoor concentrations of indoor-generated pollutants, if they installed an air cleaning system documented through prior or post installation tests to remove all CoC at a sufficient rate to prevent an increase in indoor air concentrations. The rate of removal of each CoC by the air cleaner would need to be equal to or larger than the decrease in rate of contaminant removal associated with the 50% decrease in VR. The data documenting the performance of the air cleaner could be provided through suitable prior product testing performed in accordance with a standard testing protocol. Alternately, the user of the EIAQP could, in theory, demonstrate through measurements that they have reduced sources of all CoCs by 50%, although due to the large number of potential sources these measurements would be technically challenging. While the EIAQP is still complex relative to the VR procedure, users of the EIAQP would not need to select RELs or perform a subjective survey. A variant on this scheme, an improved IAQ procedure (IIAQP), would require modest improvements in IAQ, relative to the application of the VR procedure. This variant would provide a measure of safety in case the air cleaning or source control measures do not perform as well as expected.

Risks of IAQPs and ventilation rate procedures

These are inherent risks in the broader adoption of the IAQP. If the users select source control measures or air cleaning procedures that do not work as well as expected, IAQ may be degraded. In addition, if new sources of contaminants are introduced into the building, prior established source control or air cleaning technologies may no longer be sufficient. However, the current VR procedure also does not assure that good IAQ is maintained. The current VR procedure places no constraints on indoor pollutant source strengths and does not required use of high efficiency particle filters. Also, many buildings designed to meet the VR procedure often fail to actually supply the specified minimum amount of outdoor air supply. Thus, no practical ventilation and IAQ standard will always deliver good IAQ.

CONCLUSIONS

1. In a sample of 13 retail stores, VRs generally exceeded the minimum requirements in California's Title 24 Standards; however, in a majority of stores, concentrations of selected VOCs exceeded stringent RELs.
2. Based on models, increased VRs were generally ineffective for controlling indoor particle concentrations. Experimental data indicated that outdoor air was often the dominant source of particles. Enhanced particle filtration or indoor particle source controls were indicated as the preferred methods of controlling indoor particle concentrations.
3. When ASHRAE's IAQP was applied, in 11 of 13 stores, the minimum VRs needed to maintain concentrations of CoC, below stringent RELs, were higher, often substantially higher, than the minimum VRs specified in Title 24. Thus, application of the IAQP would only enable reduced VRs and associated energy savings when indoor contaminant source control or gas phase air cleaning was implemented.
4. In two of 13 stores, all CoCs could be maintained below stringent RELs while providing less ventilation than specified in Title 24, without implementation of contaminant source control or gas phase air cleaning.
5. When applying the IAQP in 10 of 13 stores, formaldehyde control was the driver for the IAQP VR when California's stringent REL of 9 $\mu g\ m^3$ was employed. In the remaining three stores, the IAQP VRs were dictated by acetaldehyde or octanal. Even when using the NIOSH REL of 19.6 $\mu g\ m^3$ for formaldehyde, formaldehyde remained the driver for the IAQP VR in many buildings.
6. In the study of a Big Box store, more than 80% of simulated shoppers were satisfied with IAQ at all three VRs, including one VR below the minimum VR specified in Title 24. Changes in VR had a small and inconsistent impact on the level of satisfaction with IAQ.
7. Improved versions of IAQPs would, at a minimum, specify: a list of CoCs; RELs for each CoC; a method for assessing satisfaction with IAQ; and a minimum level of acceptability for IAQ.

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Appendix A

A1: Calculation of IAQP ventilation rate for VOC's

A detailed mass balance model for the indoor concentration of a specific size and composition of particles is given by Thatcher et al (2001). A simplification of this model that includes terms for mechanical filtration, and assumes no indoor generation, re-suspension or change of particle size, is given by Equation A1.

$$\frac{dC_I}{dt} = \lambda_I (PC_O - C_I) + P_H \lambda_{VR} C_O - P_{AF} \lambda_{SYS} C_I - C_I k_i + E \qquad \textbf{Equation A1}$$

Where: λ_I is the AER due to infiltration(h^{-1}), P is the penetration factor from infiltration, P_H is the penetration factor via the HVAC system, P_{AF} is the penetration factor through HVAC recirculation that accounts for particle removal by filters and deposition in the duct system, k_i (h^{-1}) is the deposition rate in the room, C_I is the indoor contaminant concentration (μg/m^3), C_O is the outdoor concentration (μg/m^3), and E is the indoor emission rate (μg/m^3•h).

Where mechanical ventilation is not present, the model can be reduced to Equation A2

$$\frac{dC_I}{dt} = \lambda_I (PC_O - C_I) + E - C_I k_i = \lambda_I PC_O - C_I (k_i + \lambda_I) + E \qquad \textbf{Equation A2}$$

For gas phase contaminants, if we assume negligible depositional, filtration or penetration losses, then the steady state mass balance model can be described by equations A3 and A4.

$$0 = \lambda_I (C_O - C_I) + E_{SS} \qquad \textbf{Equation A3}$$

$$\mathrm{E}_{ss} = (C_I - C_O)\lambda_I \qquad \textbf{Equation A4}$$

Where: E_{ss} is the steady state indoor emission rate (μg/m^3•h), C_I is the indoor concentration (μg/m^3),

The steady state outdoor air VR required to limit contaminant concentration levels to the respective reference exposure level (REL) was calculated using a simple mass balance model, given by equation A5, which assumes that the steady state emission rate (μg/m^3•h) for each contaminant is independent of the VR.

$$\lambda_{IAQP} = \frac{\mathrm{E}_{ss}}{(C_{REF} - C_{ref\_O})} \qquad \textbf{Equation A5}$$

Where: λ_{IAQP} is the IAQP-based minimum AER (h^{-1}), C_{REF} is the REL concentration for each contaminant (μg/m^3), C_{ref_O} is the reference outdoor contaminant concentration (a subset of which are given in Table 2).

A2: IAQP calculation of emission rate decreases needed to meet RELs

A calculation was made of the percentage reduction in indoor sources of contaminants that would be necessary in order to limit indoor concentrations to RELs.
Equation A4 can be used to calculate the ratio of the steady state emission rate under current conditions E_{ss}, and the emission rate required to limit indoor concentrations to C_{ref}, given by E_{new} shown as Equation A6, with store ventilation rates assumed constant.

$$\frac{E_{new}}{E_{ss}} = \frac{C_{ref} - C_O}{C_I - C_O}$$ **Equation A6**

The required percentage reduction in indoor contaminant emission rates is therefore given by:

$$\text{Percent emission reduction } \% = 100 \times (1 - \frac{E_{new}}{E_{ss}})$$ **Equation A7**

A3: Calculation of IAQP ventilation rate using particle mass

Four of ten study buildings typically used mechanical ventilation with filtration. Figure A13 represents the mechanical ventilation scenario where ventilation air enters into the building, is mixed with return supply air, filtered and then returned to the occupied zone. Contaminant mass gains by the zone are shown in blue, while losses are colored red.

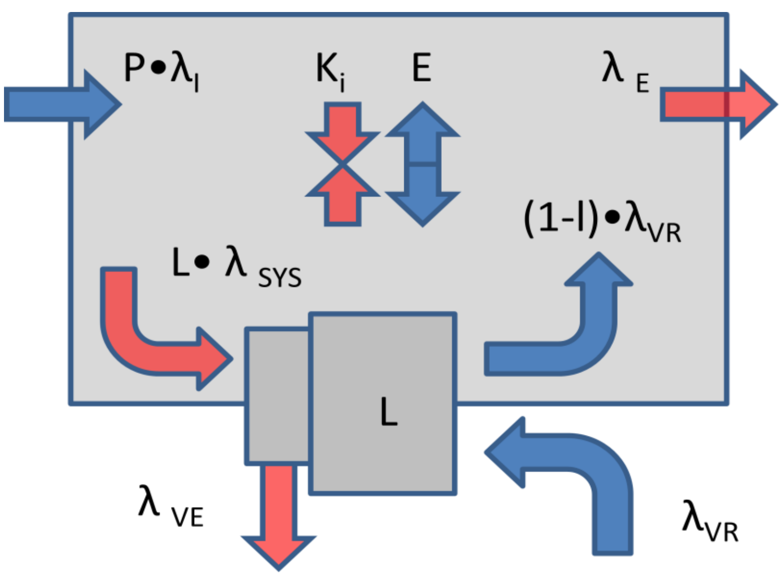

Figure A16 Mass balance flow diagram

Where: λ_I is the infiltration AER, λ_E is the exfiltration AER, λ_{VR} is the mechanical ventilation AER, λ_{VE} is the mechanical ventilation exhaust AER, λ_{SYS} is the mechanical system recirculation AER, P is the infiltration penetration factor, k_i is the first order deposition loss coefficient, L is the filtration efficiency and E is the indoor emission rate ($\mu g/m^3 \cdot h$).

From equation A1, assuming that the HVAC penetration factor P_H is driven by the filtration efficiency L, and that re-circulated air passes through the same filter as the ventilation air, the mass balance calculation for this scenario is as follows:

$$\frac{\partial C_I}{\partial t} = C_O(\lambda_I \times P + \lambda_{VR}(1-L)) - C_I(\lambda_{SYS} \times L + \lambda_E + k_i + \lambda_{VE}) + E$$ **Equation A8**

Where: C_O is the outside air contaminant concentration, and C_I is the indoor air contaminant concentration.

From the conservation of mass, the sum of the ventilation air and infiltration entering the building equals the sum of the ventilation exhaust, as given in equation A9.

$$\lambda_I + \lambda_{VR} = \lambda_E + \lambda_{VE}$$ **Equation A9**

Under steady state conditions, substitution of equation A9 into equation A8 can be used to solve for the emission rate E.

$$E = C_I(\lambda_{SYS} \times L + \lambda_I + k_i + \lambda_{VR}) - C_O(\lambda_I \times P + \lambda_{VR}(1-L))$$ **Equation A10**

PM2.5 and PM10 contaminant source strengths were calculated for each of our ten study buildings using constants based on published data. Table A11 gives the values of constants required to calculate contaminant source strengths.

Table A11 Mass balance calculation constants

Constant	Value	Description	Reference
F_{SF}	4.6 (5.1, 4.0) l/s•m^2	Measured recirculation rate per unit floor area	Persily 2008, Bennett 2011 (see summery Table A14 for details)
k_i	$K_{2.5} = 0.13$ (1/h) $K_{10} = 0.54$ (1/h)	First order deposition rate coefficient	Riley 2002
P	1 (Open door) 0.6 (façade infiltr.)	Penetration factor	Thatcher et al (2003), Wallace, (1996), Mosley, et al., (2001).
L	(PM10, PM2.5) MERV 8: (0.18, 0.24) MERV15: (0.7, 0.74)	Filtration efficiency	Riley 2002, Fisk 2003
$\lambda_{I\,[ACH]}$	0.215 (0.17-0.26)	Infiltration rate	Emmerich 2005

The first order particle deposition loss rates and the particle removal efficiencies of the filters are based largely on Riley et al (2002). They used models with experimental validation of elements to predict particle depositional loss coefficients and particle removal efficiencies of ASHRAE 40% and 85% (approximately equivalent to MERV 8 and MERV13 filters), for an office building scenario. Presented loss coefficient estimates took account of particle size distributions for PM2.5 and PM10. The estimates also took account of filters' tendency to preferentially remove the particles that most readily deposit on surfaces. Assuming offices are 75% urban and 25% rural, we used data from this paper to calculate weighted average deposition coefficients of 0.13 h^{-1} for PM2.5 and 0.54 h^{-1} for PM10.

Additionally, Riley et al (2002) estimated particle filter removal efficiencies for PM2.5 and PM10 in new ASHRAE 40% and 85% filters (approximately equivalent to MERV 8 and 13 filters). These results, listed in Table A12, account for particle size distributions and the curves of filter efficiency versus particle size. In practice, average efficiencies of filters installed in buildings are expected to be higher than the results for new filters; as filters are used, their particle removal efficiency increases substantially. Trends of the increase in filter efficiency with filter loading are shown in Hanley et al (1994) [Figure 7]; filters with an initial minimum efficiency of about 20% at 0.2 micron (roughly MERV 9) were shown to increase to a 60% minimum when half loaded with particles, and to an 80% minimum when fully loaded; Figure 6 in Hanley et al (1994) shows a filter with an initial minimum efficiency of 0.7 at 0.2 microns (approximately MERV 15), increasing to 90% when half loaded with particles and to 97% when fully loaded. Based on the assumption that surveyed filters were on average half way through their replacement cycle, an estimate of installed filtration efficiency is given in Table A13.

Table A12 Particle removal efficiency by PM size for new filters

	Efficiency%	
	PM2.5	**PM10**
MERV 8	6	8
MERV 13	56	59

Table A13 Particle removal efficiency by PM size for installed filters

	Efficiency%	
	PM2.5	**PM10**
MERV 8	18	24
MERV 13	70	74

Fisk et al (2003) presents filter removal efficiency curves for a range of filters categorized by ASHRAE dust spot efficiency ratings. Figure 1 (Fisk 2003) shows that, for the range of particle sizes that dominate the PM2.5 and PM10 categories, there is no significant difference in the filtration efficiency between a MERV 13 and MERV 15 filter. Consequently, the adjusted MERV 13 filtration efficiency in our mass balance model was used for building G01 which had a MERV 15 filter installed.

For each of the 13 study buildings, an estimate of the mechanical recirculation rate (λ_{SYS}) was calculated, based on reported typical supply air change rates (λ_{SUPPLY}), minus an estimate of the mechanically supplied outside air ventilation rate (λ_{VR}), as per Equation A11. The estimate of λ_{VR} was based on the store-specific measure of the whole building ventilation rate, minus a reasonable estimate of infiltration, Equation A13.

$$\lambda_{SYS}[ACH] = \lambda_{SUPPLY}[ACH] - \lambda_{VR}[ACH] \quad \textbf{Equation A11}$$

Where:

$$\lambda_{SUPPLY}[ACH] = \frac{F_{SF}[m^3 / h \bullet m^2]}{Height[m]}$$ **Equation A12**

$$\lambda_{VR}[ACH] = \lambda_{WBVR}[ACH] - \lambda_I[ACH]$$ **Equation A13**

Where: λ_{WBVR} is the measure whole building ventilation rate for each store, λ_I is the infiltration ACR, and F_{SF} is the supply flow rate in $m^3/(h \bullet m^2)$.

Rearrangements of equations A10 and A1 can be used to calculate the indoor concentrations over a range of mechanical and natural ventilation rates using equations A14 for buildings with mechanical ventilation and filtration and A15 for buildings without mechanical ventilation or filtration, respectively. Indoor concentrations of PM2.5 and PM10 were calculated using a range of ventilation rates bound by zero and the mechanical system supply air flow rates. Reference outdoor particle concentrations (Table 1) were used as reference maximum outdoor air concentrations C_{ref_O} in the mass balance models.

$$C_I = \frac{E + C_{ref\_O}(\lambda_I \times P + \lambda_{VR}(1-L))}{(\lambda_{SYS} \times L + \lambda_I + K_i + \lambda_{VR})}$$ **Equation A14**

$$C_I = \frac{\lambda P C_{ref\_O} + E}{(k_i + \lambda)}$$ **Equation A15**

Indoor contaminant source strengths were then used to determine the VR required to limit indoor particle concentrations to below California EPA REL of 12 µg/ m^3 for PM2.5 and 20 µg/ m^3 for PM10. For each building an IAQP-based VR was found that resulted in an indoor concentration that met guideline reference levels. Indoor contaminant source strengths were then used to determine the VR required to limit indoor particle concentrations to below California EPA reference exposure levels given by C_{ref}. Equation A10, for buildings with mechanical ventilation and filtration, and A1 for buildings without mechanical ventilation or filtration can be rearranged to solve for the minimum ventilation rate λ_{IAQP_VR}.

$$\lambda_{IAQP\_VR} = \frac{E + C_{ref\_O}(\lambda_I \times P) - C_{ref}(L\lambda_{Supply} + \lambda_I + k_i)}{(C_I(1-L) + C_{ref\_O}(L-1))}$$ **Equation A16**

$$\lambda_{IAQP\_VR} = \frac{C_i k_i - E}{(PC_{ref\_O} - C_i)}$$ **Equation A17**

The same process was then used to find a value for L that resulted in indoor concentrations that meet guidelines, assuming CA-Title 24 VRs were applied in the building.

$$L = \frac{E + C_{ref\_O}(\lambda_I \times P + \lambda_{VR}) - C_{REF}(\lambda_I + K_i + \lambda_{VR})}{(C_{REF} \times \lambda_{SYS}) + (\lambda_{VR} \times C_{ref\_O})}$$ **Equation A18**

To calculate the percentage reduction in particle emission rates required to meet RELs, assuming CA-Title 24 VRs, equation A10 can be applied using the relevant particle REL as for $C_{I.}$

$$E_{new} = C_{REF}(\lambda_{SYS} \times L + \lambda_I + k_i + \lambda_{VR}) - C_O(\lambda_I \times P + \lambda_{VR}(1 - L))$$

Air Recirculation rates

Table A14 gives the outdoor air fraction, and total mechanical recirculation rate corrected for outdoor air fraction, categorized by key building type. The mechanical recirculation rate was assumed to be the measured supply rate based on data collected during the SMCBs study using the Tracer Airflow Measurement System (TRAMS) method (Wang, 2005), minus the measured outdoor air fraction. Mechanical supply rates were scaled proportionally where only a proportion of the supplies were measured.

Table A14 Air Recirculation rate summary from the Small and Medium Commercial Building Study (Bennett, et al. 2011 Appendix D Table 1-40)

Building ID-Type	**OA %**	**Recirculation MV l/s•m²**	**Retail**	**Office**	**Resta-urant**
Building #5 Office	0	1.74		1.74	
Building #7 Gas	0	6.86			
Building # 8 Retail	0	2.43	2.43		
Building #9 Retail	0	3.56	3.56		
Building #10 Retail	0	5.66	5.66		
Building # 12 Health	0.18	20.08			
Building # 13 Office	0	4.96		4.96	
Building # 14 Office	0	3.88		3.88	
Building # 15 Office	0.19	0.73		0.73	
Building # 16 Office	0	8.57		8.57	
Building # 17 Restaurant	0.28	4.24			4.24
Building #18 Gym	0.37	2.14			
Building #20 Retail	0	4.41	4.41		
Building #21 Government	0.36	11.05			
Building # 22 Day Care	0.15	4.58			
Building # 25 Gym	0.08	10.11			
Building #26 Restaurant	0.28	8.41			8.41
Building #27 Restaurant	0.36	5.17			5.17
Building # 29 Restaurant	0.22	7.68			7.68
Building # 33 Office	0.06	7.70		7.70	
Building # 35 Gas	0	8.97			
Building # 37 Gas	0	6.26			
Building # 39 Dentist	0	13.42			
Building # 40 Restaurant	0	6.19			6.19
Mean	**0.11**	6.62	**4.01**	4.60	6.34
StdDev	**0.14**	4.21	1.37	3.14	1.72

A4: Calculation of indoor source contaminant fraction

Using a method presented by Klepeis (1999) indoor pollutants originating from indoor emissions, C_{in_I}, and from outdoor sources, C_{in_O}, were considered separately for our model scenario. Mass balance equations for indoor generated and outdoor sources are given by equations 19 and by 20 respectively. The sum of the contributions from the two sources equate to the total indoor particle concentration, equation 21.

$$\frac{dC_{in\_I}}{dt} + (\lambda_{SYS} \times L + \lambda_I + K_i + \lambda_{VR})C_{in\_I} - E = 0$$ **Equation 19**

$$\frac{dC_{in\_O}}{dt} + (\lambda_{SYS} \times L + \lambda_I + K_i + \lambda_{VR})C_{in\_O} - (\lambda_I \times P + \lambda_{VR}(1-L))C_O = 0$$ **Equation 20**

Where:

$$C_I = C_{in\_I}(t) + C_{in\_O}(t)$$ **Equation 21**

Assuming a steady state scenario for our cumulative particle mass measurements, equation 19 can be expressed as equation 22. Equating equation 22 to equation 10 and rearranging, gives the indoor concentration of contaminants from indoor sources shown in equation 23.

$$(\lambda_{SYS} \times L + \lambda_I + k_i + \lambda_{VR}) \times C_{in\_I} = E$$ **Equation 22**

$$C_{in\_I} = C_I - \frac{(\lambda_I \times P + \lambda_{VR}(1-L))C_O}{(\lambda_{SYS} \times L + \lambda_I + k_i + \lambda_{VR})}$$ **Equation 23**

The ratio of the proportion of PM2.5 and PM10 contaminants that originate from indoor sources: $\frac{C_{in\_I}}{C_I}$ was calculated for each study building.

Appendix B

Human subject demographics

Figure A17 provides a histogram of age distribution for each study week.

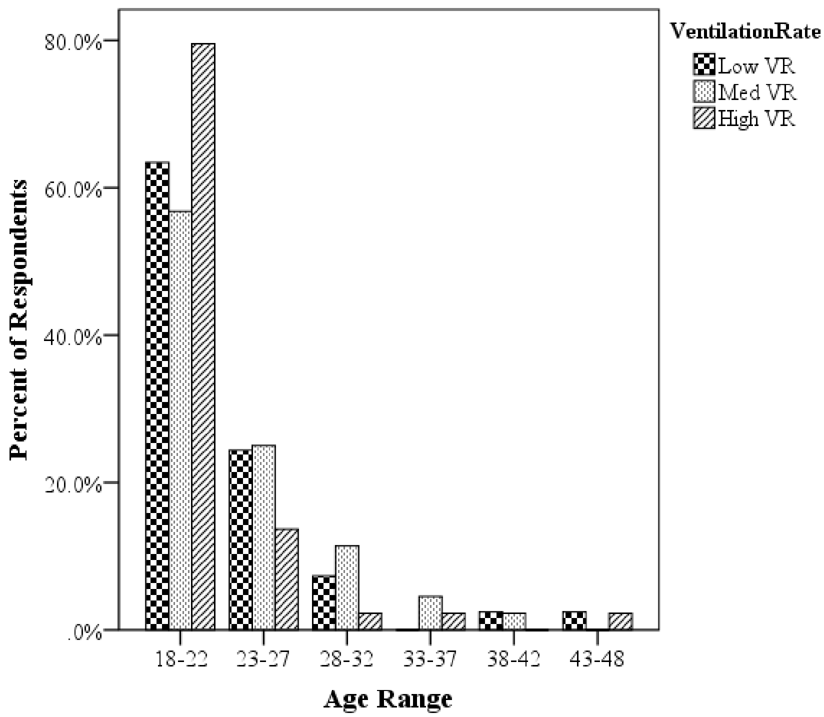

Figure A17: Distribution of the ages of respondents grouped according to age range and arranged by week.

Table A15 gives demographic factors by ventilation rate.

Table A15: Percentages of respondents according to demographic factors by ventilation rate

Demographics			
Variables	Low Ventilation Rate	Medium Ventilation Rate	High Ventilation Rate
Male	29.3%	38.6%	56.8%
Female	70.7%	61.4%	43.2%
Employee	17.1%	15.9%	25.0%
Self-Employed	2.4%	0.0%	4.5%
Student	75.6%	77.3%	70.5%
Others(s)	4.9%	6.8%	0.0%
Single	85.4%	93.2%	88.6%
Married	12.2%	6.8%	9.1%
Chose no answer	2.4%	0.0%	2.3%
Income			
$0-1000	53.7%	31.8%	59.1%
$1000-2499	12.2%	29.5%	9.1%
$2500-4999	9.8%	9.1%	6.8%
$5000-9999	4.9%	6.8%	2.3%
$10000 and above	0.0%	2.3%	6.8%
Chose no answer	19.5%	20.5%	15.9%

Table A16 gives subject's responses to questions on health factors.

Table A16: Percentages of respondents according to health factors by ventilation rates

Health Factors			
Variable	Low Ventilation Rate	Medium Ventilation Rate	High Ventilation Rate
Smoker	0.0%	0.0%	2.3%
Non-Smoker	100.0%	100.0%	97.7%
Asthma	5.0%	23.3%	20.9%
No Asthma	95.0%	76.6%	79.1%
No-Allergies	77.5%	66.7%	53.7%
Allergies	22.5%	33.3%	46.3%
-Chemical	0.0%	14.3%	0.0%
-Dust mite	11.1%	35.7%	5.3%
-Eczema	22.2%	42.9%	10.5%
-Hay fever/Pollen	66.7%	57.1%	68.4%
-Mold	0.0%	21.4%	5.3%
-Pets	44.4%	35.7%	21.1%
-None of the Above	0.0%	0.0%	10.5%

In response to the question "Where do you shop?", Table A17 gives the percentage of subjects that marked positively that they shop at the type of stores listed. For subjects who report shopping at large department stores, frequency data is also reported. Particular attention was paid to whether there was any significant bias in the subject's shopping habits between study weeks, which may have been a potential confounder.

Table A17: Percentages of respondents according to shopping behavior by ventilation rates

Shopping Behavior			
Variables	Low Ventilation Rate	Medium Ventilation Rate	High Ventilation Rate
Small local stores	70.7%	65.9%	70.5%
Mall or street stores	61.0%	65.9%	63.6%
Buy items online	78.0%	81.8%	65.9%
Large Big Box department stores	87.8%	86.4%	77.3%
-Once a year	0.0%	7.7%	0.0%
-Once a month	34.2%	25.6%	25.0%
-Few times a year	28.9%	28.2%	37.5%
-More than once every month	34.2%	38.5%	25.0%
-No Answer	2.6%	0.0%	12.5%
Others(s)	2.4%	4.5%	2.3%

Appendix C

Your route is as follows.
Please complete surveys in this station order. 1,2,3,4,5,Outside,6

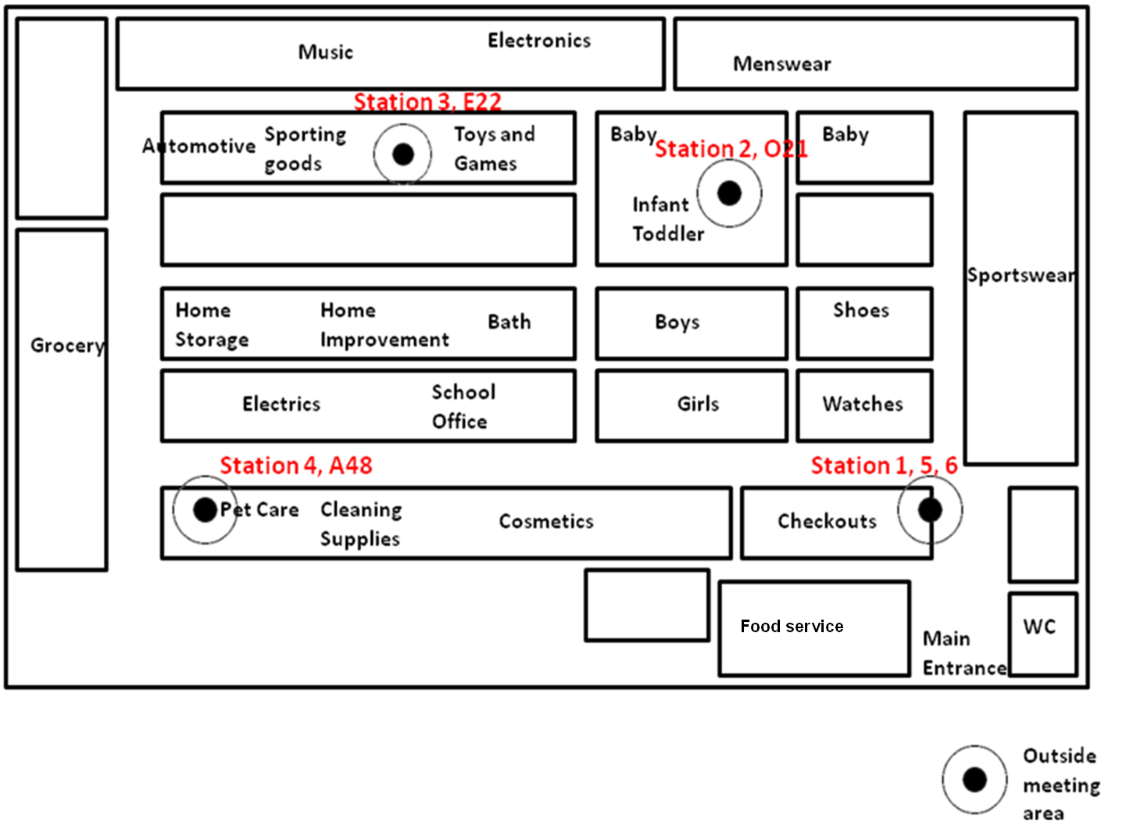

Figure A18 Subject route and map

IAQ studies in retail stores

Perceived air quality, health-related symptoms (repeated survey)

This survey is intended for study participants who have given their consent to participate in the study by signing the Consent Form. All information you provide will remain anonymous and will be kept confidential. This is a voluntary survey. We would like you to answer all the questions. However if you do not want to answer a question, you may tick the "no answer" box and move on to the next question. If you agree to participate, please write your survey ID in the box provided.

Survey ID:	**Location code:**
Location 1: Main entrance: Air quality	

Q1: How do you rate the air quality?

- Clearly acceptable
- Just acceptable
- Just unacceptable
- Clearly unacceptable

☐ **No answer**

Q2: Assess odour intensity

- Overpowering
- Very strong
- Strong
- Moderate
- Slight
- No odour

☐ **No answer**

Q3: How do you rate the temperature of the air.

- Hot
- Warm
- Slightly warm
- Neutral
- Slightly cool
- Cool
- Cold

☐ **No answer**

Figure A19 Survey form example