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Publication Date
2019-03-01

DOI
10.1016/j.buildenv.2019.03.002

Peer reviewed

LBNL-2001199

Lawrence Berkeley National Laboratory

Efficacy of occupancy-based smart ventilation control strategies in energy efficient homes in the United States

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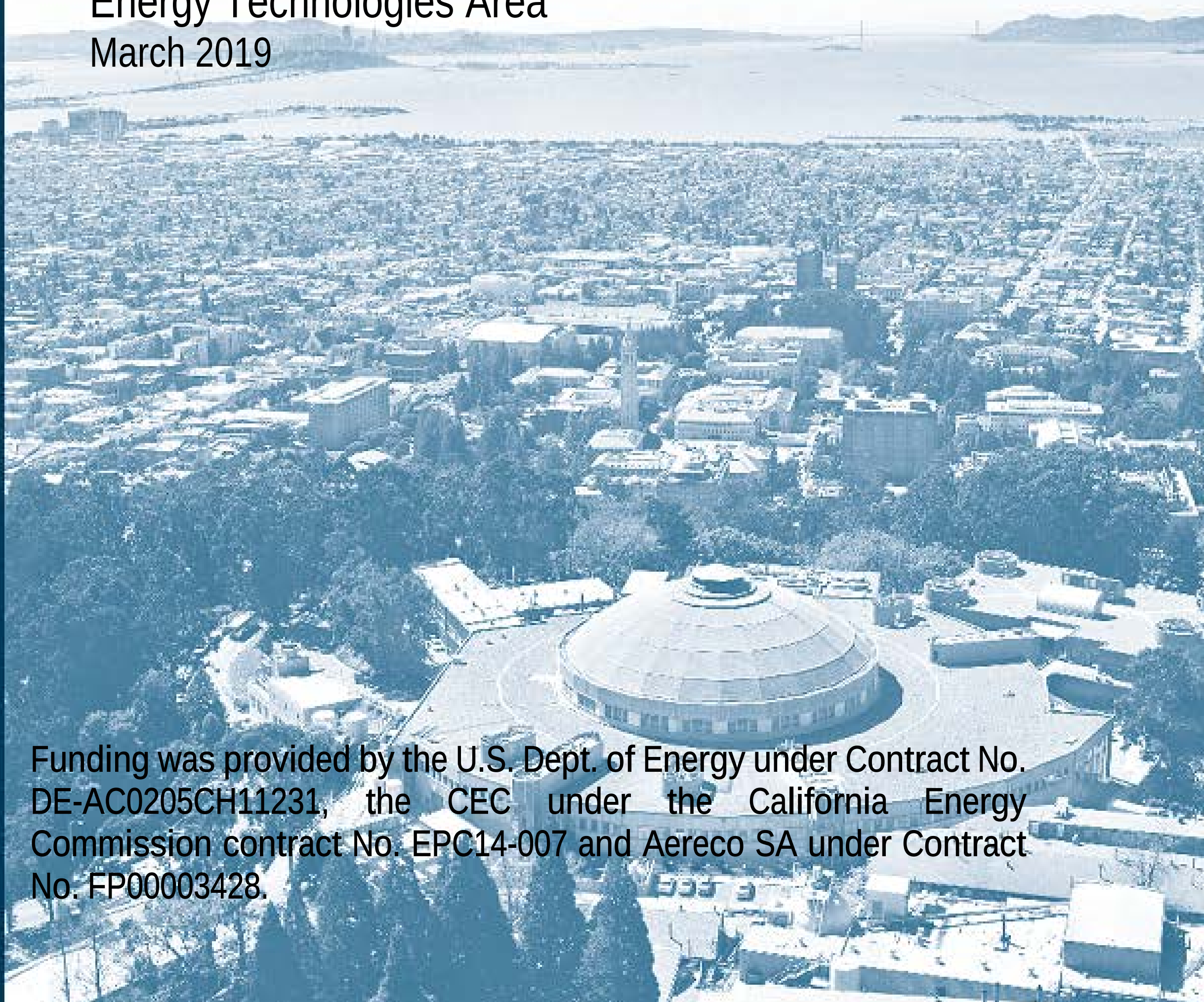
Energy Technologies Area
March 2019



Funding was provided by the U.S. Dept. of Energy under Contract No. DE-AC0205CH11231, the CEC under the California Energy Commission contract No. EPC14-007 and Aereco SA under Contract No. FP00003428.

Disclaimer

Abstract:
Proper ventilation of residences is essential for occupant health and comfort, and is responsible for a significant portion of energy consumption in homes. This study examines a method for providing adequate ventilation in homes while reducing energy consumption and peak demand: "smart" control of ventilation through sensing of occupancy and modulation of ventilation fans. We first conducted a detailed simulation study of advanced California homes with several occupancy-based ventilation control strategies. We then look at how general these results are nationally through a second simulation campaign in 15 ASHRAE climate zones. All simulations compared equivalent indoor air quality situations and assessed energy savings benefits. A key difference from previous demand-controlled ventilation strategies is that our study includes the effects of building related contaminants that are continuously emitted, irrespective of occupancy status, consistent with the requirements in ASHRAE Standard 62.2-2016. Under this new assumption, it is very difficult to extract substantial energy savings using only occupancy sensing. For the baseline strategy, savings were less than 10% of ventilation energy and sometimes negative in all cases analyzed other than leakier 2-story homes. Addition of a pre-occupancy flush period increases savings somewhat, but savings are still less than 15% other than in 2-story leakier homes.

Keywords: ventilation
smart buildings
smart ventilation
indoor air quality
residential energy efficiency

Abbreviations:

ACH50-	Air changes per hour at 50 Pascal driving force
CDD-	Cooling Days
DCV-	Demand-Controlled Ventilation
DOE-	Department of Energy
HDD-	Heating Degree Days
HVAC-	Heating, Ventilation and Air-Conditioning
IAQ-	Indoor Air Quality
Q_{fan}-	Volumetric flow rate through dwelling unit fan
RelDose-	Relative Dose
RelExp-	Relative Exposure
VOCs-	Volatile Organic Compounds

1 Introduction

Buildings account for 39% of the United States' primary energy consumption (EIA 2016), 74% of electricity consumption (EIA 2017), and 39% of carbon emissions (EPA 2013). Approximately 4% of all U.S. energy consumption is directly attributable to ventilation and infiltration, (EIA 2016). Furthermore, ventilation (especially natural ventilation) has long been known to be an effective means of offsetting other thermal loads in buildings, such as heat dissipated by occupants and equipment, and thus its effect on energy consumption is even greater.

Ventilation and its resultant effect on indoor air quality also has profound consequences for human health. Airborne fine particles ($PM_{2.5}$) alone are associated with a variety of adverse health outcomes including lung cancer and cardiopulmonary mortality (Pope et al., 2002; Anderson et al., 2011; Stolzel et al., 2007; Health effects institute, 2013; Utell et al., 2002). A causal relationship has been established and mechanisms identified between fine particle exposure and heart disease (Brook et al. 2010). A review attributed on the order of 1,000 useful years of life lost per 100,000 people as a result of exposure to fine particle in residences (Logue et al. 2012). Among gas-phase pollutants, formaldehyde was recently identified as a human carcinogen (International Agency for Research on Cancer, 2006) and exposure to formaldehyde in indoor environments is responsible for 10-1,000 useful years of life lost per 100,000 people (95% confidence, Logue et al. 2011). The sources of formaldehyde in buildings are building materials, primarily wood-based products, and these sources are emitting whether the building is occupied or not. The levels of formaldehyde in homes are often at levels of concern (Offerman 2009; Chan et al 2016). Offerman (2009) found that in the sample of 108 new homes in California studied,

> "For formaldehyde, 98% of the homes exceeded the Chronic and 8-hour RELs of 9 $\mu g/m^3$, 59% exceeded the ARB indoor air guideline of 33 $\mu g/m^3$, and 28% exceeded the OEHHA Acute REL of 55 $\mu g/m^3$."

Similar results have been found in Australia (Dingle and Franklin 2002; average of 22.8 ppb), Hong Kong (Guo et al. 2009; average of 112 $\mu g/m^3$), and France (Marchand et al. 2008; average of 32 $\mu g/m^3$). Therefore, any health-based approach to ventilation in newer California homes (the subject of the current study) needs to include formaldehyde and other contaminants that are continuously emitted.

Decades of research has been conducted and public programs enacted to reduce the amount of energy use attributable to building operation, which almost always begins with improving building envelopes such that air and energy exchange across the envelope is reduced. This is finally being done widely because of updated building codes and green building program incentives. For example, roughly 30% of newly constructed homes in the U.S. received a Home Energy Rating Score (HERS) in 2017, with an average score of 62—38% more efficient than a new home built in 2006 (RESNET 2018). When buildings are sealed, and insulation and window performance are increased, proper ventilation becomes: 1) a larger driver of total building energy consumption and 2) more important from a health perspective. New solutions are needed to optimize the tradeoff between ventilating to reduce exposure to indoor contaminants and reducing air flows to save energy.

One such solution is occupancy-based control of ventilation. This has been used for many years in commercial buildings and in European dwellings and is often called demand-controlled ventilation (DCV) (Guyot et al. 2018a and 2018b). The controls are usually based on detecting occupancy through CO_2 or humidity measurements and turning ventilation systems off (or to a minimum air flow) when buildings or dwellings are deemed to be unoccupied. A key assumption behind this type of control is that the generation of contaminants is due to occupants themselves. This can be human bioeffluents (that create odor), moisture due to breathing, or contaminants such as particles and chemicals from cooking and cleaning activities.

In their review of CO_2-based DCV, Emmerich & Persily (2001) underline the limitations inherent in using CO_2 because of its inadequacy as an overall indicator of IAQ, especially for pollutant emission from sources other than occupants, such as building materials and furnishings. We make a few distinctions between occupancy-based smart ventilation control and many other DCV strategies (Emmerich & Persily, 2001; Fisk & De Almeida, 1998; Raatschen, 1990). First, occupancy-based control in this study could be enabled by any of several sensing technologies, including infrared, motion sensors, smart phone network detection, smart meter analytics, simple timer-based scheduling, etc. Second, we account for contaminant emissions that are not associated with occupants, and lastly we ensure that the controlled system will provide the same exposure to a generic indoor contaminant during occupied hours as a continuously operating fan compliant with ventilation standards (an approach known as equivalency (Sherman et al. 2012)). Equivalence over an annual time period is required of time-varying ventilation patterns that comply with the ASHRAE 62.2-2016 ventilation standard.

Benefits realized in commercial buildings could translate to residences, but occupancy-based control of ventilation in residences has been studied much less. A key difference between commercial spaces and residences is the lower occupant density of residences. This means that occupant-related contaminants (such as bioeffluents) are less important. In theory, systems could be controlled to a low level or turned off completely during unoccupied periods, but this allows the build-up of contaminants that are not bioeffluents or related to human activity in the space (e.g., formaldehyde, many VOCs, contaminants of outdoor origin, etc.). This was shown by Hesaraki & Holmberg (2015), who showed that for unoccupied periods exceeding 4-hours in a new home, VOCs rose to unacceptable levels.

In addition, some contaminants related to human activities can be emitted in the home when occupants are no longer present, e.g., cleaning chemicals and their reaction offspring (Destaillats et al. 2006). More recently, in some European countries, DCV has been used in energy saving strategies for residences that are part of building energy standards (for a summary of these strategies and standards see Guyot et al. (2018a and 2018b). Occupancy-based control of the type that is designed to maintain equivalence with the ASHRAE 62.2 ventilation standard has only been practiced in one field study of which the authors are aware (Martin et al. 2018), which found minimal benefits.

This study examines the impact of the assumptions about indoor contaminant sources when examining occupancy-based ventilation controls. Almost all current controls assume that all contaminant emissions happen only during occupancy. We have taken an alternative approach to account for contaminants associate with the building materials and household contents (such as formaldehyde) that are emitted at all times. This could have a large potential impact on the implementation of occupancy-based controls in ventilation system design, building energy codes and indoor air quality standards. In the current study, we explore these issues through a detailed simulation campaign looking at several control strategies and the resulting energy savings and IAQ ramifications.

2 Scope and Objectives

This study first looks at the savings available through different occupancy-based control strategies in four California climate zones spanning the range of California climates. We use detailed co-simulation of EnergyPlus and CONTAM (Dols, Emmerich and Polidoro 2016) for two reference buildings which conform to California's 2016 Title 24 Energy Efficiency Standard (California Energy Commission 2016) and attempt to refine control strategies in order to provide energy savings and peak demand reduction. We then attempt to assess the generality of the California results through a second simulation campaign using C++-based REGCAP simulations conducted in 15 ASHRAE Climate Zones across the United States.

The scope of the work presented herein is limited to operation of advanced homes with dedicated ventilation that meets ventilation standards (in this study we used ASHRAE 62.2-2016). All work done herein assumes a single well-mixed zone with continuously and constantly emitted contaminants with no other sources or removal mechanisms others than air exchange. Multi-zone strategies and strategies enabled by sensing of individual pollutants will be explored in later work. The simulated homes were typical of energy efficient homes in new construction in California and the rest of the US. The key building performance characteristics are the envelope air leakage that leads to natural infiltration (that contributes to overall air exchange and pollutant dilution) and higher than average heating and cooling equipment efficiencies compared to a typical home.

The objectives of this study are to:

1. Assess the energy savings available with different strategies for occupancy-based dynamic control of ventilation systems in homes compliant with California Building Energy Efficiency Standards (California Energy Commission 2016) - also known as and referred to herein as Title 24.
2. Expand the analysis to include high performance homes across the United States
3. Develop control refinements that increase effectiveness (such as pre-occupancy venting), as well as climate specific recommendations.

3 Methodology

This study used a modeling approach that allowed us to control and systematically vary various parameters related to ventilation and infiltration: primarily weather, smart control strategies, air tightness and occupancy patterns. The modeling allowed for detailed energy calculations, as well as estimates of IAQ. A key issue is to ensure that we are comparing control strategies that provide the same indoor air quality. Without this we can simply trade less ventilation (and reduced IAQ) for increased energy savings. To ensure that IAQ is the same in each case, we used the metric of equivalency, described presently.

3.1 Equivalency

This study leverages the theory developed over the past decade to allow for dynamic control of ventilation, referred to as "equivalent ventilation" (Sherman et al. 2011a; and Sherman et al. 2012). This theory uses the quantities "relative exposure" (relExp) and "relative dose" (relDose) to both assess IAQ performance of a given strategy, and to control the ventilation system in real time. The key assumption is that if a dynamic control strategy results in occupants being exposed to pollutants in integrated quantities equal to those of a baseline (constant ventilation rate) case, the dynamic strategy is "equivalent" to the simpler baseline strategy. Relative exposure values less than 1.0 mean the dynamic ventilation strategy results in lower occupant exposure, while values greater than 1.0 mean the exposure is greater than the baseline. The baseline to which strategies are compared is the constant ventilation scenario at a rate compliant with ASHRAE Standard 62.2-2016 including infiltration credits and sub-additivity of unbalanced fans, described below. For all simulations we ensure equivalence over a one-year time period using one minute time steps, although theoretically this period could be any value.

In order to calculate exposure and dose under dynamic control strategies, it is assumed that a generic pollutant is emitted at a constant rate, with no outdoor sources or removal processes other than air exchange. From these assumptions, we calculate instantaneous exposure relative to the baseline case, referred to as "Relative Exposure", according to the following equations:

$$\boldsymbol{R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t/V_{space}}} \quad (1)$$

R_i = relative exposure for time-step, i
R_{i-1} = relative exposure for previous time-step, i-1
Q_{tot} = Target ventilation rate from ASHRAE 62.2-2016, m^3/s
Q_i = Ventilation rate from the current time-step, m^3/s
Δt = Simulation time-step, seconds
V_{space} = Volume of the space, m^3

In cases where there is no real-time and scheduled ventilation, then Equation 2 is used.

$$\boldsymbol{R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}}} \quad (2)$$

An additional control constraint is that we limit the maximum relative exposure to 5 to avoid exposure to acute levels of contaminants. This is based on work by Sherman, Logue, & Singer (2011) and Sherman et al. (2012) that investigated the ratio of acute to chronic exposure limits and set the relative exposure limit on the lowest ratio for contaminants of concern in homes. This threshold is a requirement in demonstrating 62.2-2016 compliance for smart controls.

For control purposes we have found that it is useful to also include a control parameter that integrates concentrations over a period of 24 hours, which is referred to as "Relative Dose". This is calculated using the following equations.

$$\boldsymbol{d_i = r_i * \left(1 - e^{\frac{\Delta t_{rivec}}{24}}\right) + d_{i-1} * e^{\frac{\Delta t_{rivec}}{24}}} \quad (3)$$

d_i = relative dose at time-step i
d_{i-1} = relative dose at the previous time-step i
r_i = relative exposure at time-step i
Δt_{rivec} = time-step, hr.

For the real-time ventilation controllers in this study, relative exposure of occupants is only assessed when occupants are present. However, calculation of relative exposure continues through unoccupied times so that we can track occupant exposure to the higher contaminant concentrations they are exposed to upon re-entry.

To allow for the extra ventilation required to reduce contaminant levels upon re-occupancy, a larger ventilation fan flow is required than for continuous operation in all strategies. In this study we doubled the baseline, constant ventilation fan size as a reasonable compromise between how rapidly the residence recovers from the unoccupied time (that we would like to keep short to minimize the exposure to high contaminant levels) and real-life limits on practical fan sizing that could be installed in a residence. A similar outcome could be achieved by specifying a large multi-speed fan or adding an additional fan that could be used only during over-ventilation periods. Because the fan is oversized relative to what would be required for continuous operation, the fan cycles on and off during occupied hours to maintain a relative exposure of one. The larger fan operates constantly during the recovery time at the beginning of re-occupancy. For cases with longer absence times explored in the national simulation campaign, doubling fan airflow was not sufficient and controllers failed to maintain annual equivalence during occupied hours. In these cases, we increased fan over-sizing to a factor of 2.5.

We also include estimates of natural infiltration in all simulations and control schemes. For this reason, the total air exchange rate is not zero when the fans are not operating during unoccupied times. Neglecting this natural infiltration would result in much higher peak indoor concentrations at the end of the unoccupied period. Because natural infiltration depends strongly on building envelope leakage, this parameter is one of those varied in the modeling study via changes in envelope leakage. For all simulations, we calculated the natural infiltration during each time-step using the annual average effective airflow approach in ASHRAE Standard 62.2, which accounts for varying natural infiltration by envelope leakage, building height and climate zone. This annual average is constant throughout the year and does not vary with hourly weather.

In order to add infiltration and unbalanced mechanical ventilation, the sub-additivity coefficient (Φ) in ASHRAE 62.2 is employed according to:

$$\boldsymbol{Q_i = Q_{fan,i} + \emptyset\, Q_{inf,i}} \tag{4}$$

$$\emptyset = \frac{Q_{inf,i}}{Q_{inf,i}+Q_{fan,i}} \tag{5}$$

Q_{fan} is generally the flow through the dwelling unit ventilation fan.

All of these assumptions are codified in ASHRAE Standard 62.2-2016 (ANSI/ASHRAE (2016)), Appendix C, and thus all strategies proposed in this work are compliant with this standard. Unless otherwise noted, the Annual Average Method (C2.2.1) is used for assumed infiltration.

3.2 Ventilation strategies assessed

We modeled three sets of occupancy-based smart ventilation controls strategies. The first is simply turning ventilation off during unoccupied periods, which we refer to as *Unocc*. In the second we reduce ventilation rates during unoccupied periods, referred to as *Reduc*. In the last, we ventilate the house immediately before occupancy, referred to as *Flush*.

3.2.1 Off while unoccupied (Unocc)

The Unocc control is described in Table 1 below. When the home is unoccupied, relative exposure is held below 5 in order to prevent occupants from experiencing concentrations associated with acute health or comfort effects upon their return. More details on why this value is chosen are given in in M. H. Sherman, Logue, & Singer (2011) and Max H. Sherman et al. (2012). In almost all cases, the ventilation is turned off for all unoccupied times and a relative exposure of 5 is never reached.

When occupants return, ventilation is increased relative to the baseline continuous fan airflow in order to ensure that daily and annual average relative exposure is below one. Relative exposure is calculated at each time-step, but its annual average calculation includes only occupied hours. Relative dose is calculated at each occupied time-step, and is fixed at the last occupied value when the home is unoccupied.

Condition	***Fan ON Condition***
Occupied	relExp > 1 OR relDose > 1
Unoccupied	relExp > 5

Table 1 Occupancy control strategy, fan off during unoccupied times.

Figure 1 shows an example of ventilation operation under the Unocc strategy, and the resulting effects on occupant exposure and dose. Gray periods indicate times when mechanical ventilation is on and white when ventilation is off. The aqua period indicates the period over which the home is unoccupied. At the beginning of the day when occupants are home, relative exposure is controlled to near one by cycling the ventilation fan on and off. When occupants leave, exposure is allowed to increase, with relative exposure increasing to around 2.7 before occupants return. When occupants return they are exposed to elevated contaminant levels and the relative dose increases above 1.0. To compensate for this increased exposure, a recovery period begins, during which the home is ventilated more than it would be in the baseline case. Relative exposure is rapidly reduced below 1.0, but increased ventilation continues until relative dose (24-hour integrated exposure) is also below one. This ensures that the daily-integrated exposure is less than 1.0. This additional relative dose requirement is an essential part of achieving an annual average exposure of one.

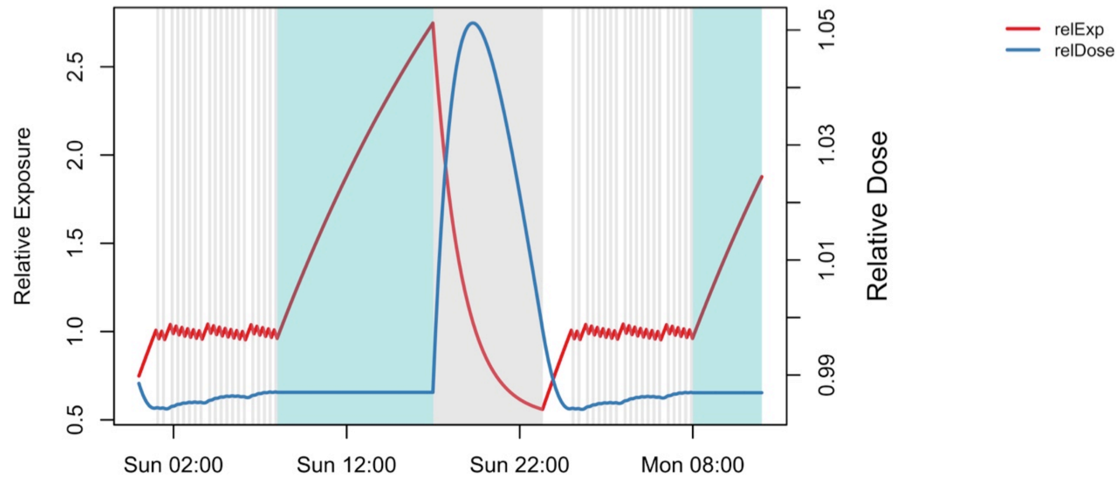


Figure 1. Illustration of Occupancy control operation with 1st shift occupancy schedule. Ventilation fan periods highlighted in light grey, unoccupied period in aqua.

3.2.2 Ventilation reduced while unoccupied (Reduc)

One improvement to Unocc strategy may be to reduce ventilation rates during unoccupied periods rather than eliminating ventilation completely during these periods. Mortensen, Walker, & Sherman (2011) suggest that for a variety of cases, occupancy-based ventilation control is most effective when the ventilation rate during unoccupied times was between 0.13 and 0.4 of the constant system, with a value of 0.35 being near optimal for the cases we are simulating. We thus analyzed a strategy that operated the continuous fan airflow at 0.35 times the baseline rate during unoccupied time periods. This approach will reduce the peak exposure and reduce the time to recover from this peak. This should reduce the average ventilation rate required to maintain exposure below one, thus saving energy.

Condition	***Fan ON Condition***
Occupied	relExp > 1 OR relDose > 1
Unoccupied	Q_{fan} = 0.35 x baseline continuous $Q_{62.2}$

Table 2 Occupancy control strategy, fan at 35% of ASHRAE 62.2 continuous Q_{fan} airflow during unoccupied times.

3.2.3 Pre-occupancy flush out (Flush)

Lastly, we investigated the inclusion of a period prior to the return of occupants in which the home is quickly flushed with ventilation air. This strategy may reduce the recovery period and save energy over all. We have reproduced a figure from Less & Walker (2017) demonstrating typical relative exposure patterns in an occupancy controller with no pre-venting, 1- and 2-hour pre-occupancy flush outs in Figure 2. No ventilation air was provided during unoccupied periods.

This shows how the flush reduces peak exposure to the occupants (at 17:00), lessens the over-ventilation period, and shifts the over-ventilation recovery period in time. For example, in the 9-

hour absence pattern detailed in Figure 2 the occupants return home at 17:00, and this controller would turn the fan on continuously starting at 15:00 for a 2-hour flush out. This approach should reduce occupant peak exposure, lessen the recovery period and save energy. For the California homes we tested a 1-hour flush and for the other homes in the US we evaluated both 1 and 2-hour flushes.

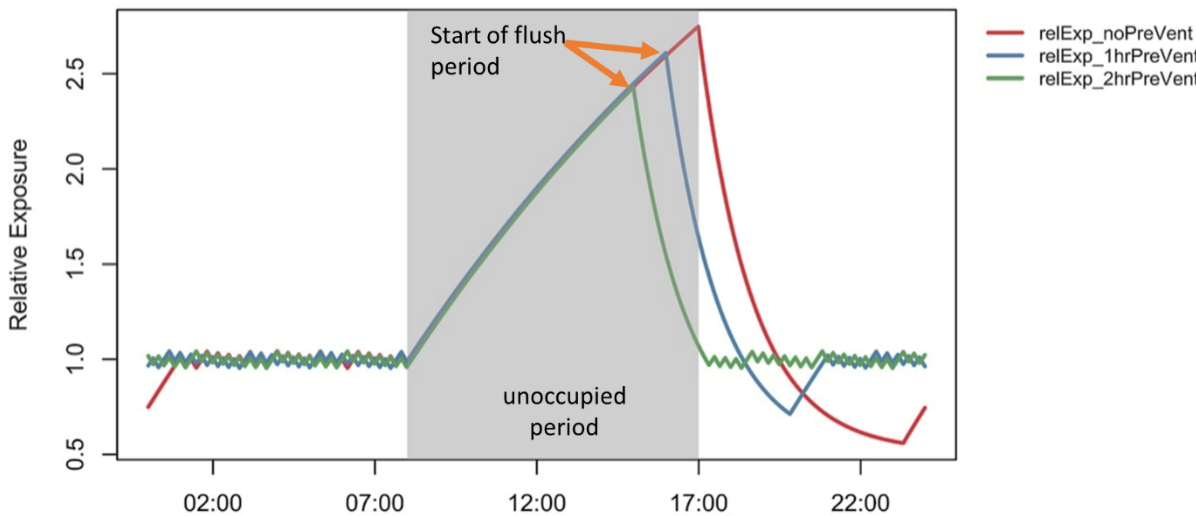


Figure 2. Relative exposure with no, one- and two-hour pre-occupancy flush out periods. Unoccupied period highlighted in light grey. Reproduced from Less & Walker (2017).

3.2.4 Occupancy Patterns

We assumed three different occupancy patterns to assess these control types. Occupancy schedules are continuous, 1st and 3rd shift, and a 1st Shift Extended pattern (1st Ext). The shift schedules have 9-hour workday absences (8am - 5pm and 9pm - 6am, respectively) and continuous weekend occupancy. Extended 1st Shift assumes an 8am-10pm unoccupied period and 10am-12pm and 6pm-8pm unoccupied period on the weekends. All patterns are idealized and are intended to be roughly consistent with typical workday patterns.

This corresponds to the normal work/school schedule for many households. It is a simplified version of that found in Hendron and Engebrecht (2010) that was developed for the US DOE Building America program. Similar profiles can be found in Kontar and Rakha (2018), University of Southampton (2016), Johnson (1981). This occupancy profile also aligns with the temperature profile used in the energy simulations that are taken from the California Energy Commission Building Energy Efficiency Standards (Title 24) and with many energy use profiles published in the literature."

3.3 Modeling methodology and simulation campaign

In order to assess the savings available with occupancy-based ventilation control of residences in California and the United States as a whole, we combine the results of two research projects. Two different simulation platforms were used: the California simulations used a CONTAM/EnergyPlus co-simulation process (Dols, Emmerich and Polidoro 2016) whereas the US Climate zones were simulated using LBNL's ventilation simulation software REGCAP. The REGCAP simulation tool was used to predict the ventilation and energy performance. It combines detailed mass-balance models for ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. The details of this model have been presented elsewhere (Iain S. Walker, 1993; Iain S. Walker & Sherman, 2006; I.S. Walker, Forest, & Wilson, 2005), along with validation summaries of house and attic air, mass and moisture predictions.

Together they create a full picture of the advisability of occupancy-based control of ventilation in the United States. Leakage distributions, wind pressure coefficients and shelter factors were all aligned identically between the REGCAP and CONTAM (Dols, and Polidoro 2015) models. We performed cross-checks between the two simulation approaches, and under identical driving forces (wind pressures and temperatures) we verified the CONTAM/EnergyPlus model had airflow rates within 1% of REGCAP.

After the models were developed, we performed a series of verification exercises to ensure that the models performed exactly the same as previously validated models. We previously extensively validated an in-house simulation platform with regards to air exchange rates and interaction of ventilation system with enveloped air exchange. This validation is detailed in Walker and Wilson (1998) and Walker, Forest and Wilson (1995). For the purposes of this work, we simply applied the same driving conditions (indoor-outdoor temperature difference and façade wind pressures) for ten different representative conditions and verified that the exact same air exchange rates were calculated by each simulation platform. As EnergyPlus and CONTAM have been extensively validated over the past few decades (Emmerich 2001), and the ventilation was the only system modified in the course of this work, we considered this sufficient validation.

California Simulations

- We simulated homes matching the specifications of the two Title 24 single-family prototype units, whose properties are made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 Title 24 energy code. Details of the prototypes can be found in Nittler & Wilcox (2006).
- We created detailed models of two prototype homes: a 1-story 195 m^2 (2,100 ft^2) prototype home and a 2-story 251 m^2 (2,700 ft^2) prototype home, with forced air space conditioning systems.
- Heating and cooling systems were sized using ACCA Manual J load calculation procedures, with thermostat schedules set to meet those specified in the Alternative Calculations Manual of the Title 24-2016. Several deliberate deviations were made from the Title 24 prescriptive path prototypes. We improved the equipment efficiencies and we did not model any duct leakage, as ducts were assumed to be inside the conditioned envelope. Equipment efficiency was increased beyond prescriptive minimums to Seasonal

Energy Efficiency Ratio (SEER) 16 air conditioner and 92 Annual Fuel Utilization Efficiency (AFUE) gas furnaces in order to align with standard new construction practice.

- We parametrically varied airtightness among values of 1, 3, and 5 Air Change per Hour at 50 Pa (ACH_{50}) to assess the effect of envelope leakage and resulting natural infiltration. The ventilation systems are compliant with ASHRAE 62.2-2016 that includes with infiltration credits and sub-additivity adjustment, with exhaust fans used in 3 and 5 ACH_{50} and balanced fans in the 1 ACH_{50} cases. The combination of infiltration and mechanical systems was modeled using CONTAM. The resulting airflows were then used in EnergyPlus. See Appendices A and B for more information on leakage distributions, infiltration calculations, and ASHRAE 62.2-2016 calculations of interest to this work.
- For each home and climate in California, we modeled the thermal interaction of the building with its environment and internal loads with EnergyPlus. EnergyPlus (U.S. Department of Energy 2018) is a comprehensive building operation simulation tool supported by the Department of Energy (DOE), which has sophisticated models for building heat balance, HVAC operation, lighting, etc. Inputs to the EnergyPlus models for the two prototype homes were generated with BEopt (Christensen et al. 2006), and then inputs were modified where better information was available, e.g. Air Conditioning Contractors of America Manual J (ACCA 2016) for system sizing.
- We simulated home performance in locations that covered a broad range of climatic conditions in California. Table 3 gives the climatic design data for 4 representative cities, from the harshest Blue Canyon (CZ16) to the very temperate Oakland (CZ3), and Riverside (CZ10) in southern California that represents a location with greatest growth in new construction and higher cooling loads.
- All results assume infiltration is calculated according to the procedure given in ASHRAE Standard 62.2 for annual average effective infiltration.
- In all simulations, interior spaces are assumed to be well-mixed at all times and ventilation airflows are added as a generic contribution to the mass and energy balances of the home air. In practice this ventilation air could be provided by any of several devices including a dedicated whole-house fan or a combination of existing ventilation devices.
- No actual pollutants are modeled in this work-relative exposure is calculated at each time as a function of ventilation and infiltration rates only, in accordance with ASHRAE Standard 62.2 Appendix C (ANSI/ASHRAE 2016)

Table 3 Climate zone design information, including heating and cooling degree days calculated at 18.3°C reference temperatures, and heating/cooling design temperatures.

CEC Climate Zone	Heating Degree Days $_{18.3}$	Cooling Degree Days$_{18.3}$	Design Temperature (Heating/ Cooling, °C)
CZ1 – Arcata	2,658	1	0.6 / 20.6
CZ3 – Oakland	1,436	85	2.2 / 26.7
CZ10 – Riverside	1,011	888	1.7 / 37.2
CZ16 – Blue Canyon	3,174	151	-4.4 / 27.2

US DOE Climate Zone Simulations

- All simulations used a single-story, 200 m^2 (2,153 ft^2) home with three bedrooms, two bathrooms and four occupants. The homes are compliant with the energy and performance specifications of the U.S. DOE Zero Energy Ready Home program. The small difference in size between this prototype and the single-story California prototype is due to the different sources of information used to specify the homes: CEC publications were used for California homes and U.S. DOE publications used for the national study. These include thermally efficient envelopes (R-value in SI of 2.3-4.43 walls), high performance HVAC equipment (80 to 94 AFUE heating, SEER 13 to 18 cooling) and airtight construction (3 ACH_{50}), with the various performance requirements varying by US DOE climate zone. All DOE climate zones 1-8, including marine, moist and dry were simulated—15 in total.
- The REGCAP simulation tool was used to predict all of the variables of interest, including airflows and energy use. It combines detailed mass-balance models for ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. The details of this model have been presented elsewhere (Walker, Forest, & Wilson, 1995), along with validation summaries of house and attic air, mass and moisture predictions. REGCAP is implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance and to allow for dynamic time-based controls. REGCAP combines natural infiltration with mechanical air flows from the house ventilation system that is the subject of the ventilation controls, as well as kitchen, bathroom and dryer exhausts flows.

3.4 Calculating Ventilation Energy Savings

In each scenario, we simulated two baseline (no ventilation controller) cases: (1) with no IAQ fan, and (2) with a minimally compliant, continuous fan sized to meet the ASHRAE 62.2-2016 ventilation standard. The energy attributed to meeting the ASHRAE ventilation standard was the difference in total annual HVAC energy consumption between these two cases, which includes fan energy and building loads. The energy savings for occupancy-controlled cases were calculated by subtracting the total HVAC energy consumption for the smart control cases from the ASHRAE 62.2-2016 constant fan baseline cases. Fractional ventilation energy savings were calculated by dividing the savings by the energy required to meet the ASHRAE standard.

Equivalence-based ventilation controls commonly do not achieve an annual relative exposure exactly equal to one. The controls are imperfect and they create slight (2-3%) biases in the resulting exposure. Similarly, a continuous fan baseline also does not achieve an annual relative exposure exactly equal to one when using an unbalanced fan, due to differences in the forward vs. backwards implementation of the superposition of natural infiltration and unbalanced mechanical ventilation in ASHRAE 62.2-2016.

Thus, in order to properly normalize results with annual average relative exposure equal to one in all cases, we created a set of cases for each combination of climate zone and house prototype (two prototypes, four climates) that had no air exchange either through fans or natural infiltration. Energy consumption in these cases was deemed the “envelope-only” energy use. This envelope energy use was subtracted from the HVAC energy use for each standard case to estimate the total energy consumption added to the home by outside air exchange (including both mechanical and natural airflows). This ventilation energy was then multiplied by the annual mean controller exposure for the case, in order to estimate the ventilation energy use that would have occurred if the controller exposure was exactly 1.0.

For example, if a case was slightly over-ventilated relative to the target airflow (e.g., mean exposure of 0.98), the ventilation energy use (for both mechanical and infiltration airflows) in that case was multiplied by 0.98 to approximate the slightly lower ventilation energy use that would have occurred if exposure were equal to 1.0. This normalized ventilation energy was then added back onto the envelope-only energy use for each case, and these adjusted HVAC energy use values were used to estimate energy savings of smart controls relative to baseline continuous dedicated ventilation fan cases.

We also tested an alternative normalization approach that parametrically varied the smart control parameters in order to get controller exposure to equal 1.0, and the two normalization methods had very good agreement in predicted total HVAC energy use. So, here we present the results of the more simple method described in the prior paragraph.

4 Results

In the following section we present the results of the two simulation campaigns. We first present the results of the California study for three control strategies, three airtightness levels and two different prototypes (1-story and 2-story). We then present results of the national study to assess the generality of the California results and to assess the effect of occupancy patterns.

4.1 California results

The results of the California study for the Unocc strategy are presented in Figure 3. The Unocc strategy provided little (<8% of ventilation energy) benefit in all cases except the leakier (5ACH50) 2-story homes.

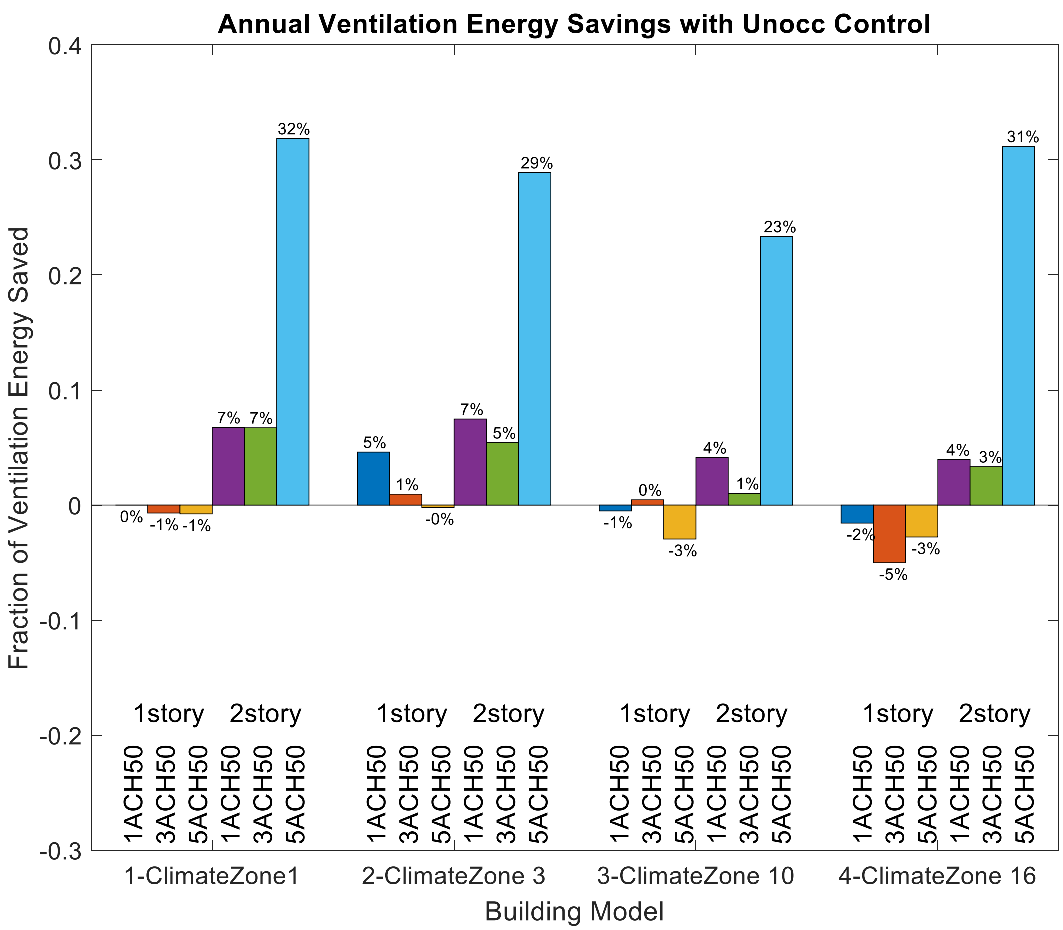


Figure 3. Calculated ventilation energy savings with Unocc control strategy for four California climate zones with various air-tightness levels and assumed prototype buildings

These results show that much of the benefit of turning off the ventilation system during unoccupied time periods is eliminated because the smart ventilation controller must over-ventilate to maintain equivalence with ASHRAE 62.2 during the recovery period immediately after occupants return home. The common pattern was for the ventilation to be off for 9-hours, and then the airflow was doubled for roughly 6-hours in order to recover and maintain equivalence, resulting in only a netreduction in daily airflow of roughly 12%. This is much less reduction compared to simply turning off the ventilation during unoccupied periods that would result in daily airflow reduction of nearly 40% (9/24). The leakier two-story homes have the greatest natural infiltration during unoccupied times, which reduces peak exposure and thus necessary over-ventilation times upon occupant return.

In many of the 1-story prototype home simulations, the Unocc strategy resulted in higher energy consumption. The 1-story homes consistently save less energy than 2-story homes because the lower natural infiltration rates in the 1-story homes increase peak exposure and increase recovery times, thus negating energy savings. The difference in peak relative exposure for the two prototypes is shown below in Figure 4. A simple linear fit is fit to the data to estimate a simple relationship between exposures in each building. Peak exposure for corresponding cases is approximately 10% less in the 2-story homes than in corresponding 1-story homes, and that peak exposures in leakier homes can be nearly half of those in tighter homes.

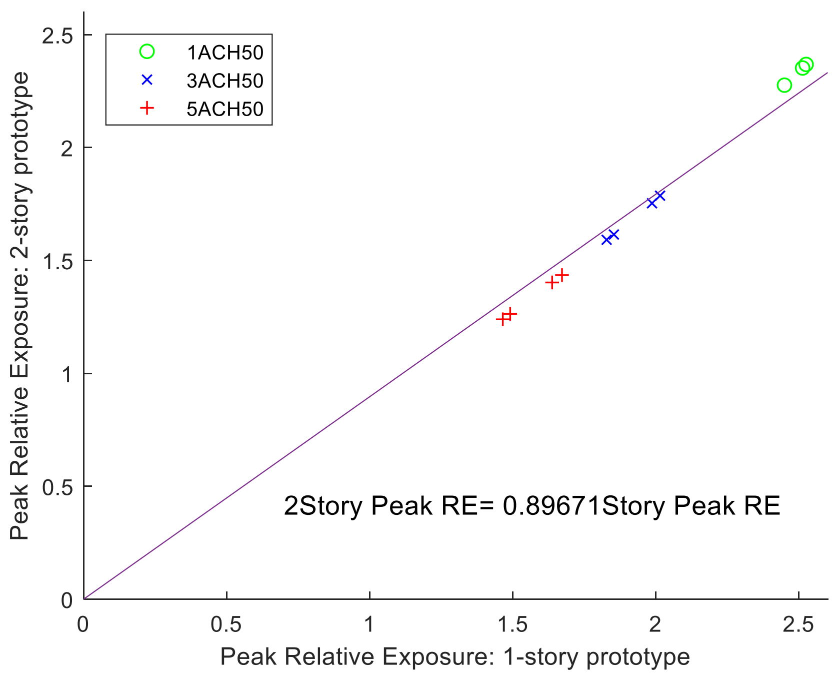


Figure 4. Comparison of peak relative exposure in one and two story prototype homes

When the ventilation systems operated at reduced air flow rather than being turned off (the Reduc strategy described in 3.3.2), we get the results shown in Figure 5. Similar to the Unocc case, savings were 10% of ventilation energy or less with the exception of leakier 2-story homes. No clear benefit is broadly evident from this strategy, and in many cases performance is reduced. This is due to the increased ventilation required during unoccupied periods. While this serves to reduce peak exposure, the resulting energy consumption is still greater.

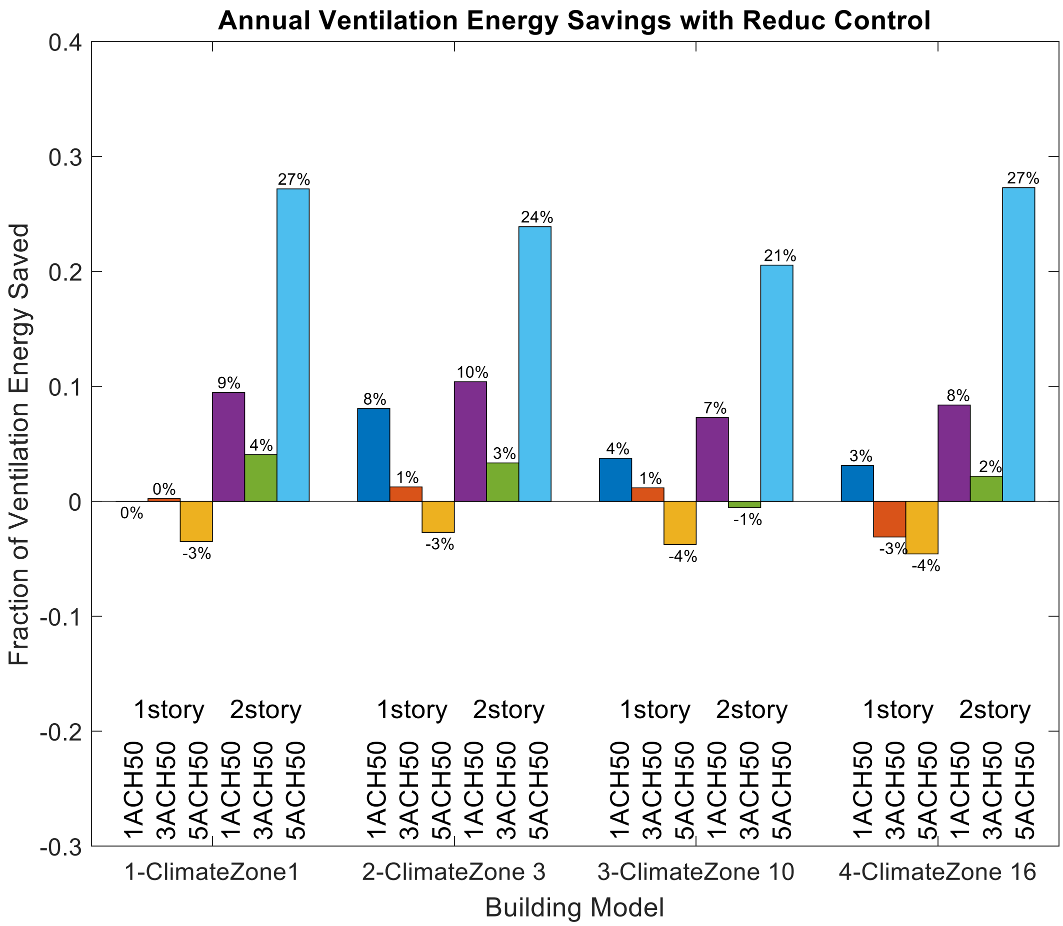


Figure 5 Calculated ventilation energy savings with Reduc control strategy for four California climate zones with various air-tightness levels and assumed prototype buildings

Figure 6 shows the results with a 1-hour flush period that occurred immediately before occupants returned home. On average there was a 5% increase in ventilation energy savings over the Reduc case, and positive savings under all scenarios compared to both the baseline and Reduc cases.

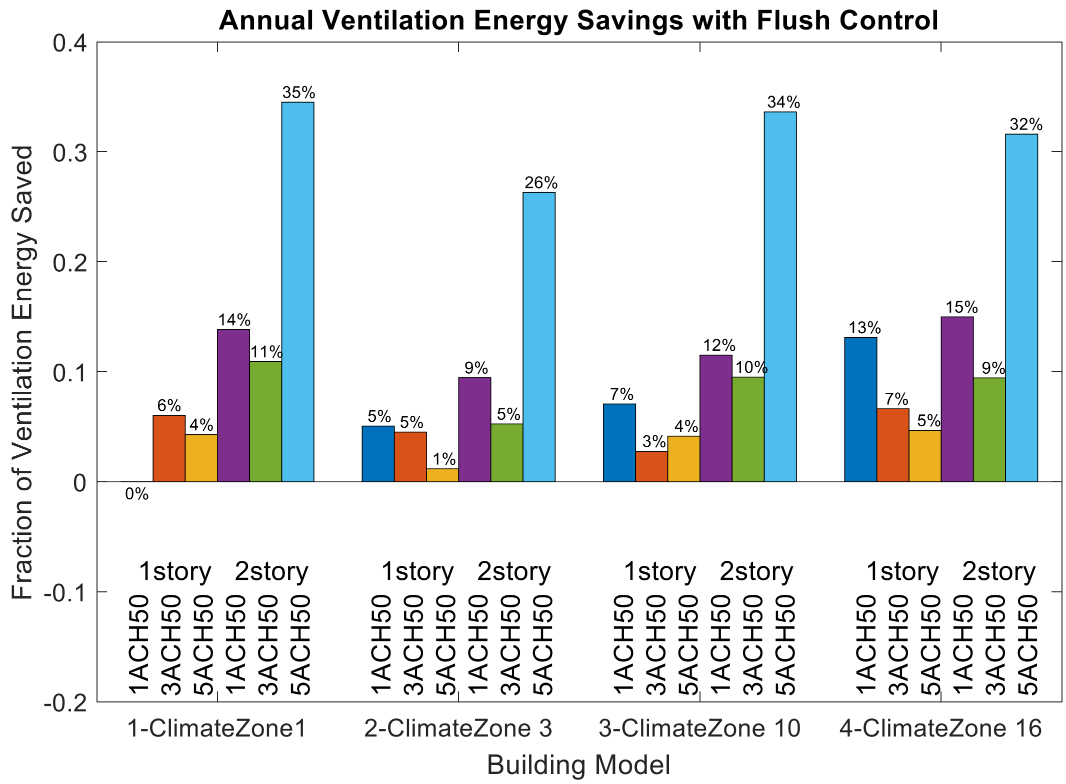


Figure 6. Calculated ventilation energy savings with one-hour Flush control strategy for four California climate zones with various air-tightness levels and assumed prototype buildings

One assumption that plays a large role in the calculation of necessary ventilation is how infiltration is modeled. In all results reported thus far, we have used the annual average effective infiltration airflows calculated in ASHRAE Standard 62.2. These are constant rates based on the effective annual infiltration rate that provides equivalent exposure to the time-varying natural infiltration rate (Turner et al. 2012). As they are average values, this approach over-estimates infiltration during low-infiltration periods and under-estimates it during high-infiltration periods. The AIM-2 model (Walker and Wilson 2011) is also available for demonstrating compliance in the ASHRAE 62.2-2016 (referred to as the Smaller Time Step Method in Section C2.2.2). This model uses real-time weather conditions paired with envelope leakage, house geometry and shelter factors to estimate time-varying infiltration airflows.

In Figures 7-9 we show the savings that were calculated with the use of the AIM-2 model. It should be noted that more information is needed for calculation of the assumed infiltration with this model (i.e. wind speed and outdoor temperatures), and thus this strategy would be less straightforward to implement. We can see that the assumption of ventilation model makes a substantial difference in climate zones 1 and 16. In Climate Zone 16 the AIM-2 model predicts significantly higher savings while in Climate Zone 1 the AIM-2 model predicts significantly less than the ASHRAE 62.2 model. However, in the vast majority of simulations savings predictions were less than 20% of ventilation energy regardless of ventilation model assumed.

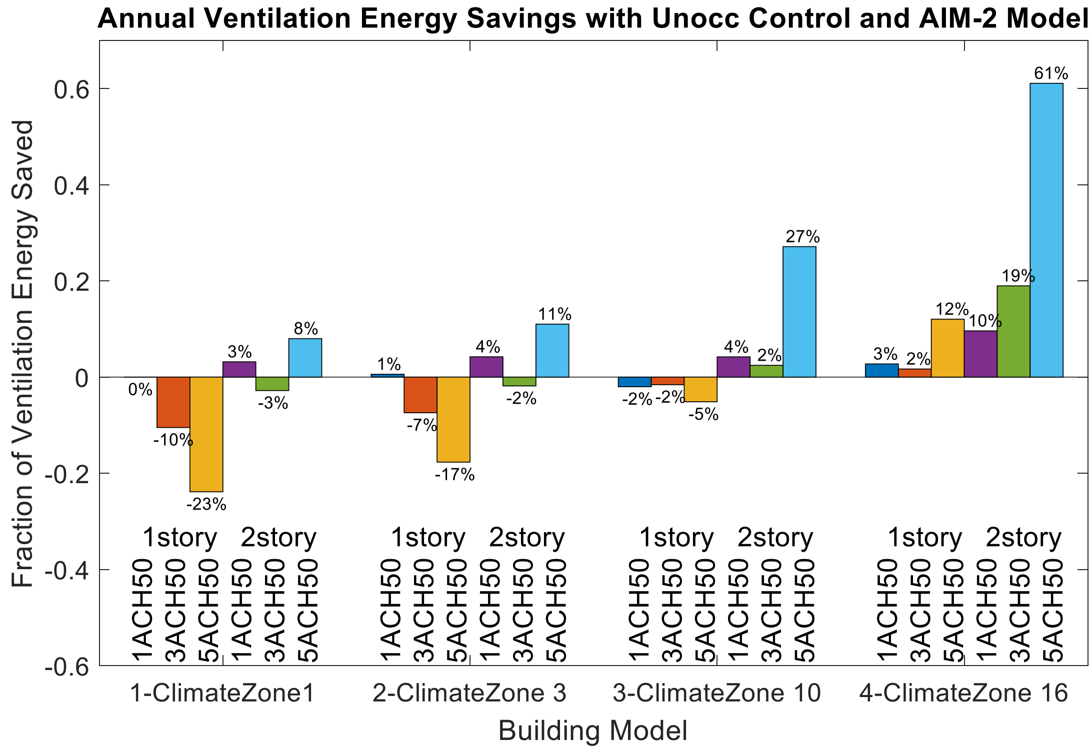


Figure 7. Ventilation energy savings with AIM-2 ventilation model and Unocc control strategy.

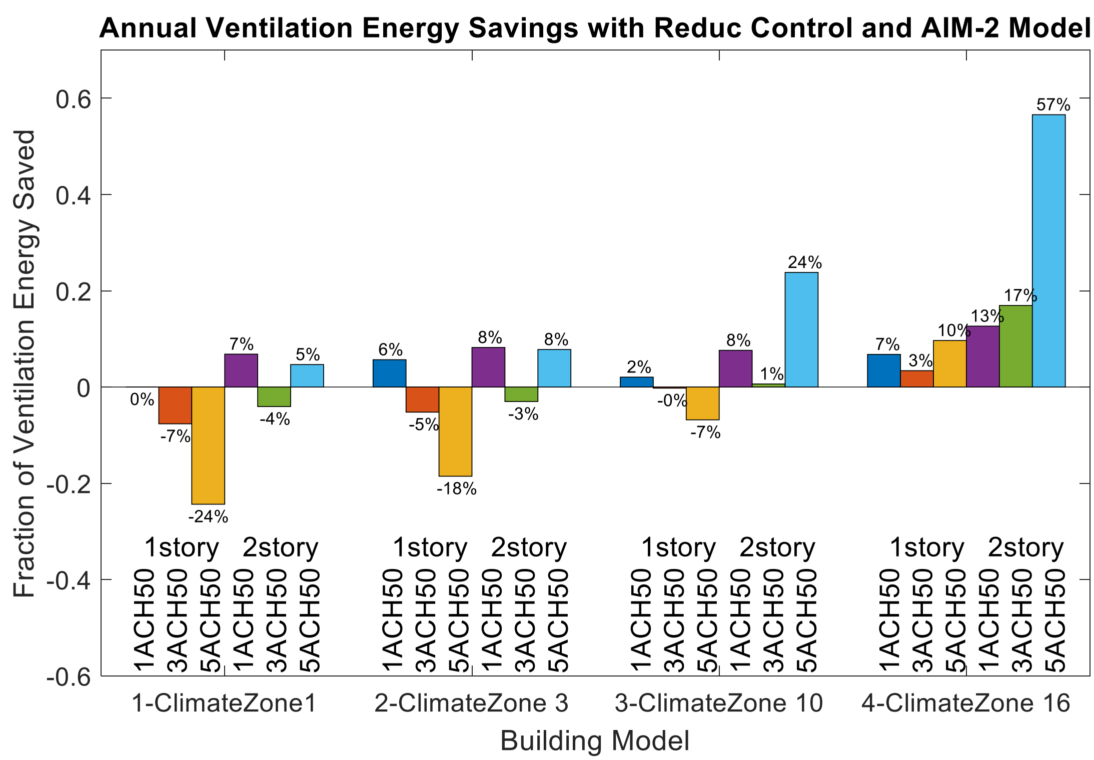


Figure 8. Ventilation energy savings with AIM-2 ventilation model and Reduc control strategy.

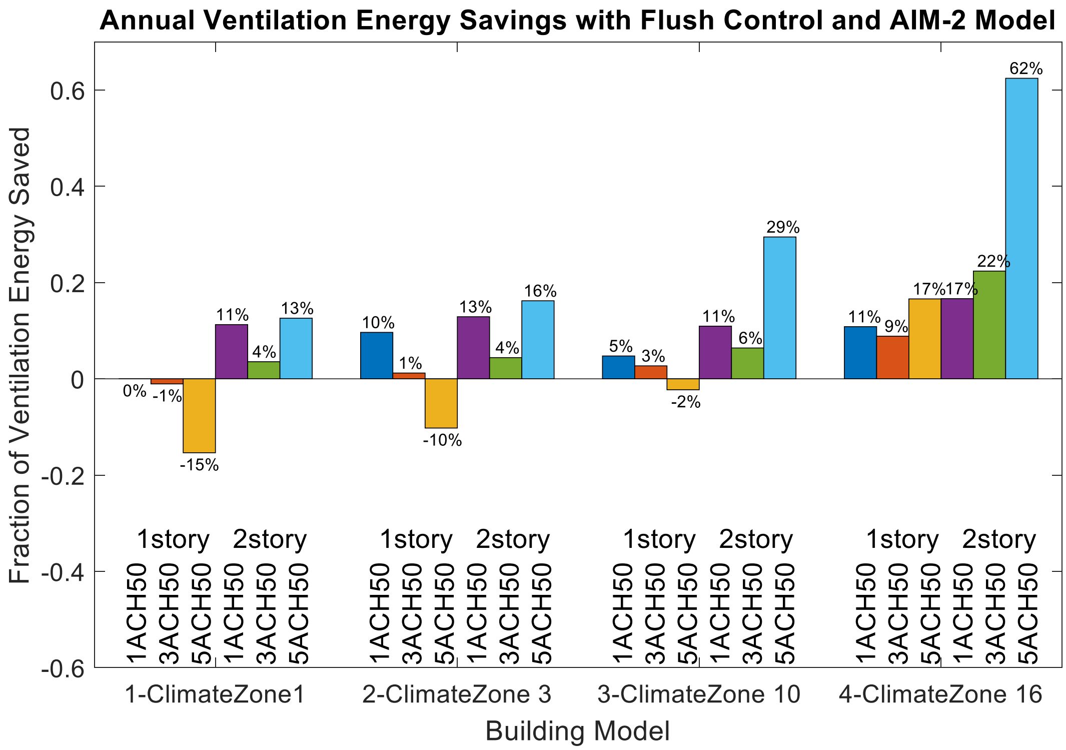


Figure 9. Ventilation energy savings with AIM-2 ventilation model and Flush control strategy.

4.2 National Study

Figure 10 shows the results for Unocc strategy applied in 15 cities across the United States. The Unocc approach gives similar result to the California simulations with less than 10% ventilation energy savings in all climates but Miami and, in some cases, increased energy use. The exceptions are in more cooling-dominated climates, like Miami. This climate variability should be an important factor when considering the use of occupancy-based controls. Increased unoccupied hours and shifting unoccupied time to be at night both significantly increased the energy savings indicating that utility of occupancy-based ventilation controls will depend strongly on the occupancy pattern for an individual household. The balanced fan gave consistently more savings.

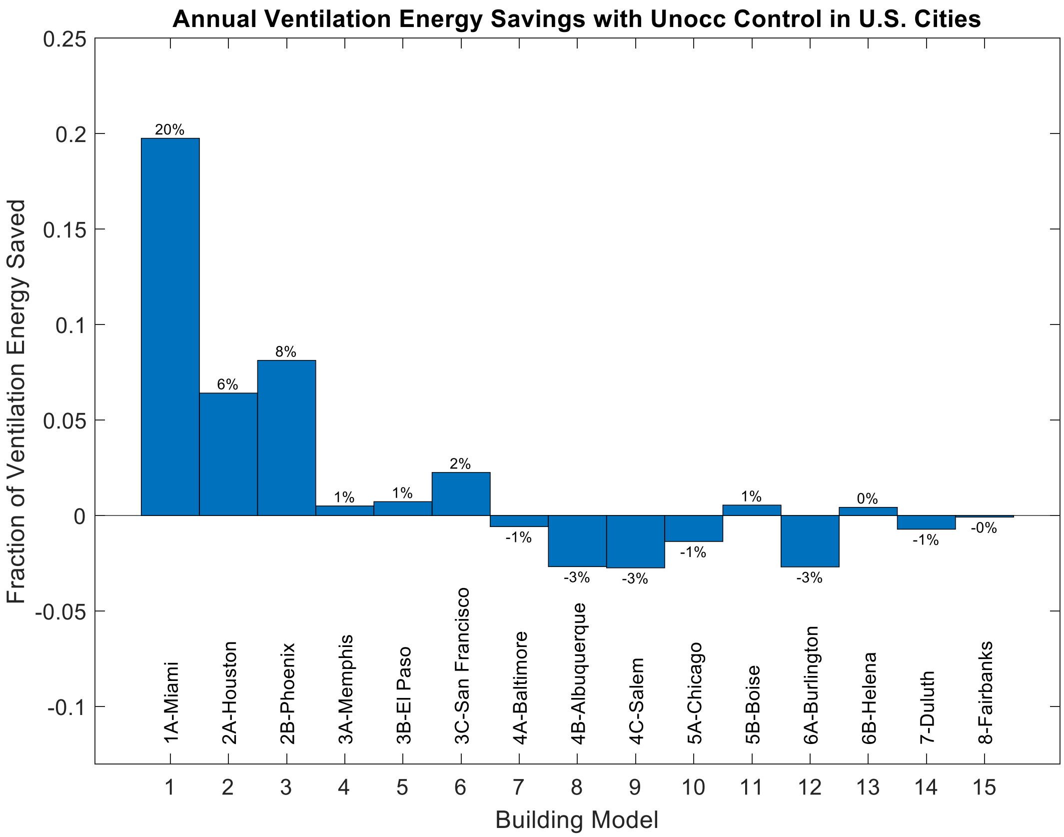


Figure 10. Calculated ventilation energy savings for the Unocc strategy applied in fifteen U.S. DOE climate zones.

We perturbed the models used in the national study to assess whether the results were dependent on the occupancy pattern assumed. We can see in Figure 11 that there were no general trends between assumed 1st shift and third shift, with some climates increasing savings and others showing decreasing savings. However, the extended first shift, with its longer unoccupied period, did see an increase in savings (average of 9%), indicating that households with longer absences are more likely to see substantial savings.

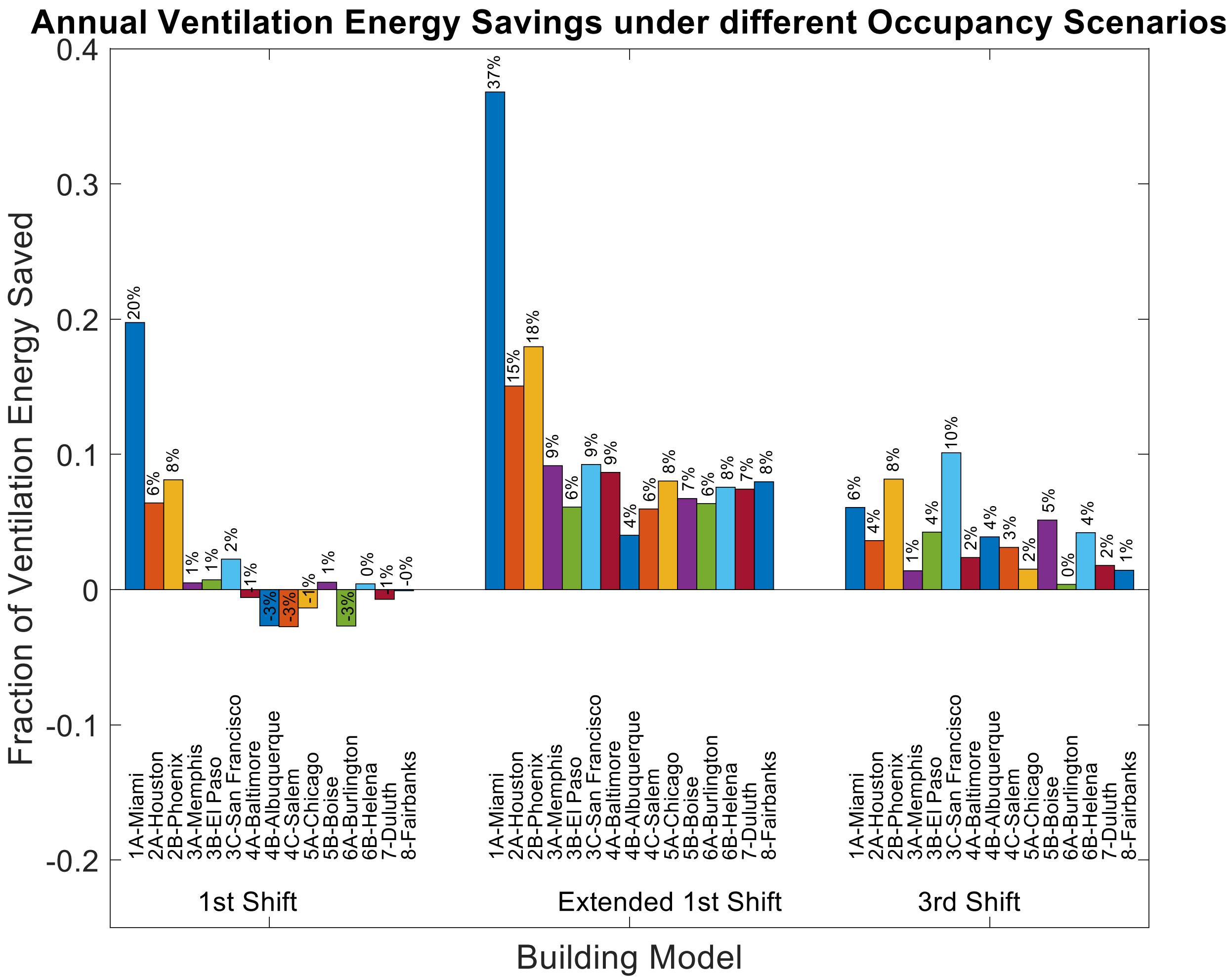


Figure 11. Calculated ventilation energy savings for the Unocc strategy with 3 different assumed occupancy patterns for fifteen U.S. DOE climate zones.

5 Discussion

We can make the following observations regarding the energy performance of these occupancy-based control strategies that indicate under what circumstances this approach may be most viable in single-family homes:

1. When occupants return from an absence, they are exposed to high contaminant levels, and the ventilation rate must be temporarily increased to recover from this exposure. This greatly limits potential savings. The amount of airflow required to recover depends on the peak exposure when occupants return home, and any feature that reduced this peak exposure also reduced the airflow needed to recover, and improved energy savings. For example, increased envelope leakage, taller homes, and climate regions with more infiltration (i.e., cold and windy), all lead to higher ventilation rates when unoccupied, lower peak exposures, and increased savings.
2. Performance is climate-dependent, due to the alignment of occupancy patterns with daily temperature patterns. Generally hotter climates have more savings, because mechanical ventilation is curtailed during the hottest hours of the day for 1st shift cases, reducing the cooling load. For most heating climates, ventilation rates are reduced during the mildest hours of the day, which limits any energy benefit. Similarly, 3rd shift ventilation savings are marginally higher, because mechanical ventilation is curtailed during colder nighttime hours.
3. Homes will benefit more the less they are occupied. This may seem like an obvious remark, but when we are finding that in some cases there are no savings, or even increases in energy, it may be that increasing unoccupied time does not automatically save energy.
4. Reducing mechanical ventilation during unoccupied hours, rather than fully curtailing it, had no clear and general benefit with most cases showing less than 10% energy savings. It reduced peak exposure and lessened the airflow required to recover after an absence, but the airflows were too high during unoccupied hours, which eroded potential savings. A further reduction in the mechanical fan airflow (e.g., 10%) might prove more effective, but was not tested in this work.
5. Turning on ventilation prior to re-entry to the home appears to be a viable strategy for increasing energy savings. The results show that a one-hour flush is a reasonable approach. To enact this strategy would require some prior knowledge of occupancy schedules (or possible remote system operation, e.g., one could turn on ventilation remotely using an internet-enabled control system). Many households are tied to work or school schedules that would make this a viable option, and many cell phones are currently equipped with geo-fencing capabilities that could facilitate such a strategy.
6. Accounting for time-varying natural infiltration rates can substantially improve ventilation energy savings in climate zones with high driving forces (i.e., extreme temperatures and wind), particularly for 2-story homes with substantial envelope leakage.

6 Conclusions

This study has shown that when we account for pollutants that are emitted by building materials and other sources while a home is unoccupied, the potential for an occupancy-based ventilation controller to save energy is limited, and can even increase energy use in some cases. This is primarily due to the time-shifting of ventilation to periods of larger indoor-outdoor temperature difference, and to the increased ventilation airflows required to balance out occupant exposure to elevated contaminant levels upon re-entry. The energy performance of occupancy-based ventilation control in homes can be improved by using control strategies that turn on ventilation an hour or so prior to re-occupancy. The energy savings are increased for cooling-dominated climates and for homes and locations with increased natural infiltration.

Further research may add nuance to these findings and suggest alternative control strategies. Future work should include investigations of the proper assumptions for contaminant emission rates when homes are unoccupied, and the sensing of individual pollutants on a continuous basis. A second phase of the work presented herein will examine this issue, and also explore the benefit of treating spaces as multiple zones.

Acknowledgments:

Funding was provided by the U.S. Dept. of Energy under Contract No. DE-AC02-05CH11231, and the CEC under the California Energy Commission contract No. EPC-15-037.

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Appendix A. Infiltration Models Used in Smart Controls—Qinf and AIM-2

Consistent with the ASHRAE 62.2-2016 standard, natural infiltration is treated in one of two ways for our real-time relative exposure and relative dose calculations. Each smart control is tested with both methods of accounting for infiltration.

First, a fixed annual effective infiltration rate can be used, referred to as Q_{inf} and calculated as in Equation A3. These values are calculated according to house geometry, leakage area and location (w_{sf} factors). This is the infiltration rate that would give the same annual relative exposure as the predicted time-varying infiltration rate, which is dependent on indoor and outdoor temperatures, as well as wind speed, direction and a host of other parameters. This effective infiltration value tends to under-predict infiltration rates when temperature differences are large or when it is windy, and it over-predicts infiltration when conditions are calm and with small temperature differences. The derivation of the current w_{sf} factors is described in detail by Turner, Sherman, & Walker (2012).

The second approach to treating infiltration in demonstrating ASHRAE 62.2-2016 compliance is to use the AIM-2 infiltration model from the ASHARE Handbook of Fundamentals, which provides real-time estimates of infiltration rates based on outdoor temperature and wind conditions. The 62.2 standard refers to this as the *Smaller Time Step Method* (Section C2.2.2). The model has been validated through field measurements (I. S. Walker & Wilson, 1998). The model inputs include house leakage area, shelter factors, wind speed modifiers, wind and stack coefficients.

The value of using AIM-2 in temperature-based smart ventilation controls is that it allows the controller to account for the fact that higher ventilation rates are in-fact occurring during times with greater temperature differences or wind. By accounting for this, the controller will reduce dedicated ventilation fan airflow rates, which should save energy. The controller will also know when natural infiltration rates are low, and it will compensate with higher IAQ fan airflows, but with less energy impact. In order for a smart controller to apply the AIM-2 model, it would need reliable, real-time outdoor temperature and wind data. This is not always possible, and smart controllers can be effective without this data. So, for each of the most promising control strategies we test, we will assess their performance using Q_{inf} and using AIM-2 infiltration methods.

At each time-step, a natural infiltration estimate is calculated as the combined wind and stack airflows. Wind airflow is estimated using Equation A1. Stack airflow is calculated using Equation A2. The combined total airflow is estimated using Equation A3. The coefficients used in the model are selected based on house characteristics, including number of stories, foundation type, presence of a flue, etc. We used model coefficients assuming slab-on grade foundation and no flue present as outlined in Table.

$$Q_w = c \times C_w(sGU_{met})^{2n} \quad \text{A1}$$

$$Q_s = c \times C_s(|T_{in} - T_{out}|)^n \quad \text{A2}$$

$$Q_{inf,i} = \sqrt{Q_w{}^2 + Q_s{}^2} \quad \text{A3}$$

$Q_{inf,i}$ = total house infiltration at time step i, L/s
Q_w = wind-induced infiltration airflow, L/s
Q_s = stack-induced infiltration airflow, L/s
c = house leakage coefficient, $m^3/s\text{-}Pa^n$
C_w = wind coefficient
s = shelter factor
G = wind speed multiplier
U_{met} = meteorological site wind speed, m/s
n = pressure exponent

Model Coefficient	***1-story***	***2-story***
Wind Speed Multiplier (G)	0.48	0.59
Shelter Factor (s)	0.5	0.5
Wind Coefficient (C_w)	0.156	0.170
Stack Coefficient (C_s)	0.054	0.078
Pressure Exponent	0.65	0.65

Table A1 AIM-2 model coefficients used in SVACH simulations.

CONTAM Envelope Leakage Distribution, Wind Pressure Coefficients and Shelter Factors

Envelope Leakage Distribution

The leakage distribution refers to the orientation, height, size and locations of the leaks in a building envelope. The distribution of leaks, primarily by height, but also by orientation, can have substantial impacts on infiltration estimates. In addition to changing infiltration airflows, leakage distributions also affect how unbalanced fan airflow combines with natural infiltration to predict whole house airflow. The leakage distributions are described in detail for the 1- and 2-story prototypes in Table and Table , respectively, including the height and size of each leak in the CONTAM models. In CONTAM, all leaks had discharge coefficients of 1.0 (a factor already accounted for in use of effective leakage area). The CONTAM envelope leakage flow elements are pictured in Figure . For the attic space, ceiling leakage was included, as were three cracks for each orientation representing unintentional attic leakage, as well as builder-installed venting to satisfy building code.

Floor height and wall leaks are evenly distributed on each of the cardinal faces of the homes, which is represented by the % values in the “Leakage Fraction, Total” vs. “Leakage Fraction, per Face” columns (the latter is simply the former value divided by 4). Five individual leaks are modeled on each of four walls, with heights evenly distributed along the total height of the walls (varies by number of stories). Overall, the 1-story homes have 25% floor height leakage, 25% wall leakage and 50% ceiling leakage (into the separately modeled attic zone), which is consistent with the default assumption of 50% ceiling leakage specified in the Title 24 2016 Alternative Calculation Method (ACM). The leakage areas in the 2-story homes have 16% floor height leakage, 52% wall leakage and 32% ceiling leakage. These values were selected to give leakage per unit wall/ceiling area roughly similar to those in the 1-story home, as well as similar leakage per linear foot of slab perimeter.

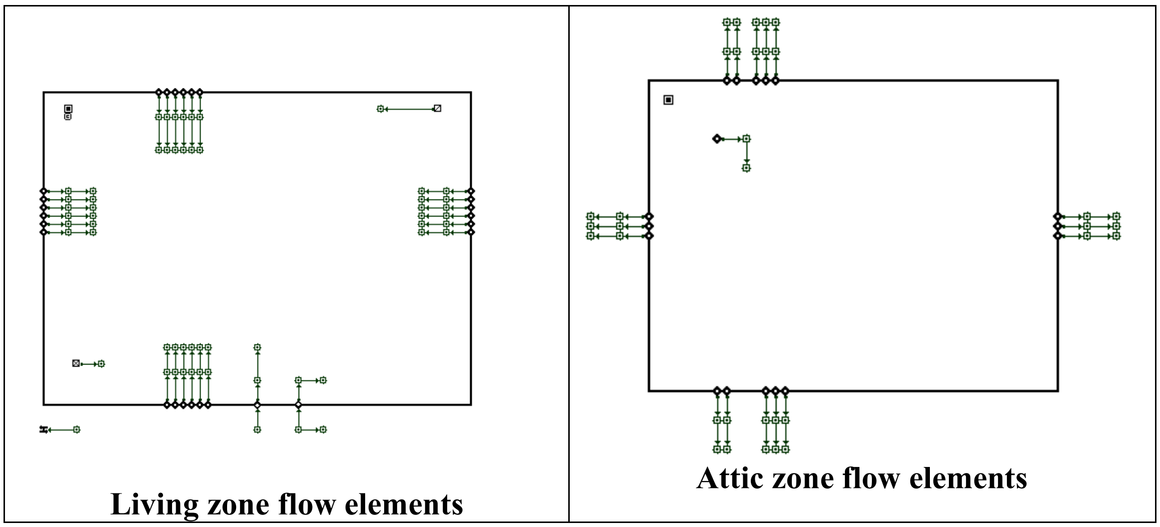

Figure A1 Location of flow elements on building envelope in CONTAM.

Leak Type	***Leak Height From Floor (m)***	***Leakage Fraction, Total***	***Leakage Fraction, per Face***	***Leakage Areas Per Leak (cm^2)***		
				1 ACH_{50}	***3 ACH_{50}***	***5 ACH_{50}***
Floor	0.0	25%	6.3%	6.64	19.91	33.18
Wall_1	0.3	5%	1.3%	1.33	3.98	6.64
Wall_2	0.8	5%	1.3%	1.33	3.98	6.64
Wall_3	1.4	5%	1.3%	1.33	3.98	6.64
Wall_4	1.9	5%	1.3%	1.33	3.98	6.64
Wall_5	2.5	5%	1.3%	1.33	3.98	6.64
Ceiling	2.7	50%	50.0%	53.09	159.28	265.47
Total		***100%***	***100%***	***106.19***	***318.56***	***530.94***

Table A2 1-story prototype house leakage distribution.

Leak Type	***Leak Height From Floor (m)***	***Leakage Fraction, Total***	***Leakage Fraction, per Face***	***Leakage Areas Per Leak (cm^2)***		
				1 ACH_{50}	***3 ACH_{50}***	***5 ACH_{50}***
Floor	0.0	16%	4.0%	5.79	17.36	28.93
Wall_1	0.6	10%	2.6%	3.76	11.28	18.81
Wall_2	1.7	10%	2.6%	3.76	11.28	18.81
Wall_3	2.9	10%	2.6%	3.76	11.28	18.81

Wall_4	4.1	10%	2.6%	3.76	11.28	18.81
Wall_5	5.2	10%	2.6%	3.76	11.28	18.81
Ceiling	5.8	32%	32.0%	46.30	138.89	231.48
Total		***100%***	***100%***	***144.67***	***434.02***	***723.37***

Table A3 2-story prototype house leakage distribution.

We customized the 2-story prototype's leakage area distribution, because the fixed 50% ceiling leakage assumption of Title 24 does not stand up to scrutiny when comparing the results for 1- and 2-story homes. For a 5 ACH_{50} home, the 1-story prototype has total leakage area of 530 cm^2, or 265 cm^2 in the ceiling. The same 2-story prototype has 722 cm^2 total leakage area, while there is 361 cm^2 in the ceiling. So, there is almost 100 cm^2 greater leakage in the ceiling, while the ceiling area in the 2-story home is roughly half that in the 1-story. This fixed approach puts a lot more leakage area in a lot less ceiling area, effectively doubling the leakage area per unit ceiling area. We cannot think of a credible reason that 2-story homes would have double the leakage area per unit ceiling area. We hypothesize that the measurements by Proctor et al. represent an average distribution including both 1- and 2-story homes in the ECO study. Unfortunately, the average distribtion may substantially misrepresent both home types—underestimating ceiling leakage fraction in 1-story homes and over-estimating it in 2-story.

The number of flow elements in the CONTAM model was chosen based on the trade-off between simulation accuracy and model complexity. We wanted to represent flow variation with orientation to adequately capture wind-driven ventilation, as well as by height in order to estimate vertical stack-driven forces due to temperature difference and height. The distribution of the cracks was based on expert understanding of typical distribution of attic leaks in California homes.

In addition to the infiltration flow elements, we also added two flow elements on the south wall to represent the whole house fan. For the balanced fan models, both flow elements are used to provide flow in opposite directions. In the unbalanced model a single flow element is used to represent an exhaust fan. No ducts were modeled in CONTAM, as they were considered to be in conditioned space, and therefore as having no effect on house air exchange with outside. The flow rate of the whole house fan is controlled by the smart ventilation controller.

Wind Pressure Coefficients and Shelter Factors

Leaks that have an orientation, such as floor height and wall leaks, are exposed to different pressures depending on their orientation and the direction of the wind. As such, CONTAM allows the user to apply either built-in or customized wind pressure coefficients, which vary by orientation. But CONTAM does not allow for use of shelter factors, which account for the effects of other nearby buildings on the wind pressures exerted on a building. Specifically, an isolated building experiences very different wind pressures than a home located in a row of other homes (as in the common block configuration in the U.S.).

We applied custom wind pressure coefficients and shelter factors for floor and wall leaks based on their orientation as detailed in Table 1. The wind pressure coefficients and shelter factors are the same as those used in the validated REGCAP heat, moisture and mass simulation model (I.S. Walker, Forest, & Wilson, 2005).

Incident Wind Angle	***Combined Wind Pressure and Shelter Coefficients – HOUSE***			
	North (0°)	***South (180°)***	***East (90°)***	***West (270°)***
30	0.531	-0.219	0.005	-0.527
60	0.261	-0.066	0.085	-0.247
90	-0.104	-0.084	0.035	-0.115
120	-0.055	0.256	0.069	-0.226
150	-0.200	0.531	0.004	-0.527
180	-0.300	0.600	-0.637	-0.650
210	-0.219	0.531	-0.527	0.005
240	-0.066	0.261	-0.247	0.085
270	-0.084	-0.104	-0.115	0.035
300	0.256	-0.055	-0.226	0.069
330	0.531	-0.200	-0.527	0.004
360	0.600	-0.300	-0.650	-0.637

Table 1 House custom combined wind pressure and shelter coefficients, by incident wind angle and surface orientation.

Attic leakage elements also had custom wind pressure coefficients, matching those used in the validated attic model implemented in the REGCAP simulation. The attic leaks do not have any sheltering and are reproduced in Table .

Incident Wind Angle	*Combined Wind Pressure and Shelter Coefficients – ATTIC*			
	North (0°)	***South (180°)***	***East (90°)***	***West (270°)***
30	-0.350	-0.277	-0.156	-0.250
60	-0.250	-0.060	-0.059	-0.284
90	-0.104	-0.085	-0.023	-0.154
120	-0.051	-0.245	-0.048	-0.259
150	-0.253	-0.350	-0.133	-0.250
180	-0.400	-0.400	-0.196	-0.200
210	-0.277	-0.350	-0.250	-0.156
240	-0.060	-0.250	-0.284	-0.059
270	-0.085	-0.104	-0.154	-0.023
300	-0.245	-0.051	-0.259	-0.048
330	-0.350	-0.253	-0.250	-0.133
360	-0.400	-0.400	-0.200	-0.196

Table A5 Attic custom wind pressure coefficients, by incident wind angle and surface orientation.

Appendix B Mechanical Fan Sizing

Baseline Fan Sizing

All baseline ventilation fans are sized according to the current calculation method in ASHRAE 62.2-2016. This means a target ventilation rate (Q_{tot}) is calculated based on home floor area and number of occupants/bedrooms as in Equation B1. An effective annual average infiltration airflow (Q_{inf}) is then estimated using the results of a blower door pressurization test as in Equation B2. Finally, a mechanical fan airflow (Q_{fan}) is calculated using the target airflow and estimated infiltration per Equation B3.

$$\boldsymbol{Q_{total} = 0.03A_{floor} + 7.5(N_{br} + 1)} \quad \textbf{B1}$$

Q_{total} = Total required ventilation rate, cfm
A_{floor} = floor area of residence
N_{br} = number of bedrooms (not less than one)

$$\boldsymbol{Q_{inf}(cfm) = \frac{NL(wsf)A_{floor}}{7.3}} \quad \textbf{B2}$$

Q_{inf} = Effective annual infiltration rate, cfm
NL = normalized leakage, derived from blower door testing
wsf = weather and shielding factor from Normative Appendix B 62.2-2016, varies by climate zone
A_{floor} = floor area of residence

$$\boldsymbol{Q_{fan} = Q_{total} - \emptyset(Q_{inf} \times A_{ext})} \quad \textbf{B3}$$

Q_{fan} = required mechanical ventilation rate, cfm
Q_{total} = Total required ventilation rate, cfm
Q_{inf} = Effective annual infiltration rate, cfm
A_{ext} = 1 for single-family detached homes
ϕ = 1 for balanced ventilation systems and otherwise: $Qinf/Qtot$

Smart Control Fan Sizing

To maintain equivalence with homes ventilated to the target airflow calculated using ASHARE 62.2-2016, smart controlled fans that time-shift ventilation rates must be over-sized. Most SVC fans are double the flow of the corresponding baseline cases. Where fans are not doubled, the Fan Size Multiplier (FSM) is noted in the control description. This multiplier is sometimes also used directly in the control development and setting of control parameters. For example, the smallest exposure value that a fan can achieve is well approximated by 1/FSM. If the FSM is 2 (double the baseline), then the steady state concentration at full fan flow would be half that in the baseline case. A triple over-sized fan could reach a minimum exposure of 1/3, etc. The lower the exposure is able to go, the more under-ventilation the controller can use to strategically save energy. For example, the target high and low exposure values used in the running median control are FSM and 1/FSM, respectively.

This approach works very well in a very airtight home, where the fan airflow is nearly equal to the whole house airflow. But in the leakier homes, the ventilation fan is only a fraction of the target ventilation rate, so doubling the fan airflow fails to double the whole house airflow. In effect, fan airflow doubles, infiltration is unchanged, and the resulting whole house flow is slightly less than doubled, and exposure is greater than the 1/FSM target (e.g., 0.5). So, the minimum exposure target used in some control types may in fact not be reachable, which skews the exposure higher than desired. This issue worsens as the natural infiltration rate (Q_{inf}) predicted using ASHRAE 62.2-2016 equations increases relative to the target ventilation rate (Q_{total}). Many of the SVC are designed to achieve an annual exposure of 0.97 (instead of 1.0) to account for just such imperfections in control structure, definitions and operation.

We expect that the sizing of the smart controlled fan will have substantial impacts on performance, with effects varying strongly by the type of control strategy and eve fan type. Less & Walker (2017) showed that when using occupancy controls, increasing the size of a balanced IAQ fan had very little impact on energy performance, though the annual average exposure went down marginally as fan size increased. They also found that using an unbalanced fan with a controller that cycles the fan on and off led to increases in annual air exchange and associated ventilation energy. This was the result of superposition effects in the combining of unbalanced airflows with natural infiltration. To summarize, unbalanced fan airflows are sub-additive with natural infiltration (see Equation B3), and the amount of additional airflow provided by a fan changes with the ratio of the fan airflow to the infiltration airflow. As the fan airflow gets larger relative to the infiltration airflow, the fan contributes more to total house airflow—it gets more credit. As the fan gets smaller relative infiltration, it gets less credit. When a larger fan cycles on and off to provide the same relative exposure as a continuous fan with lower airflow, the unavoidable result is that the average air exchange increases for the cycling fan (as does ventilation energy use). This occurs for unbalanced smart controlled fans, but would also apply to any unbalanced ventilation system operated on a timer or otherwise cycled to maintain an average airflow.

For smart controls that do not change their target exposure values or overall control approach with fan size, we expect nearly no effect for balanced fans, and moderate negative effects for unbalanced fans as their over-sizing increases. But other smart control strategies, such as some of the temperature-based controls, change their target relative exposure values based on fan sizing. In these cases, larger smart controlled fans should increase energy savings, because they allow more time shifting of ventilation than smaller.

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