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Impacts of Energy-Efficiency Retrofits on Ventilation and Indoor Air Quality in Low-Income Households

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Impacts of Energy-Efficiency Retrofits on Ventilation and Indoor Air Quality in Low-Income Households

by

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Shrestha, Prateek Man (Ph.D., Mechanical Engineering)

Impacts of Energy-Efficiency Retrofits on Ventilation and Indoor Air Quality in Low-Income Households

Thesis directed by Prof. Shelly Miller

Energy-efficiency retrofit (EER) activities can affect home ventilation rates and negatively impact occupant health in low-income households. The work discussed in this dissertation investigates in detail the impacts of EERs along with various household characteristics and environmental conditions on indoor air quality in low-income housing of Colorado. We found that the quality of EERs can vary greatly, and the distribution of annual average air exchange rates in homes with EER are not significantly different than the homes without the EERs. We also found that window weather-stripping and furnace ductwork sealing should be prioritized more than door and window caulking and foam-sealing of cracks and openings while performing EERs. Significant amount of indoor dust and odor were reported in leakier homes located close to major roads. We also found that outdoor particulate matter (PM) and black carbon (BC) were higher in concentration than indoors at least 50% of the time due to the influence of both long-range wildfire plumes and traffic emissions, and the indoor concentration of PM showed monotonic rise with increasing plume cover particulate density. Indoor nitrogen dioxide was primarily dominated by the presence of gas stove more than any other factor. We concluded that heat recovery ventilation (HRV) systems integrated with air filtration systems can greatly reduce the infiltration of PM and BC in homes, yet provide an energy-efficient way of adequate ventilation.

Dedication

This dissertation is dedicated to my late father Mr. Prakash Man Shrestha, a loving, caring, joyful, extraordinary father.

Love you *Bua*…

Acknowledgements

I am deeply thankful for the unconditional love and support from my late father Mr. Prakash Man Shrestha, my mother Mrs. Pramila Shrestha and my sister Ms. Prapti Shrestha, for helping me pursue my dreams and for carving me into the person that I am today. I especially thank my sister for helping me grow emotionally and intellectually, helping me to come to the U.S. for higher education, adjusting into a new country's culture, and being a constant source of support and encouragement. I am also thankful to all my friends, roommates, cousins, extended family, relatives and teachers in the U.S. as well as back home in Nepal for all their help and support.

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Chapter 1

Introduction

Indoor air quality (IAQ) is a matter of public health concern. We spend the majority of our time in any day in built environments, mostly our homes. The air that we breathe at our home is one of the most important sources of agents that can deposit inside our lungs and deteriorate our health. Government intervention programs aimed at reducing hazards or promoting energy efficiency that guide the building codes can directly affect the conditions in the homes that we live in. Especially, the intervention programs aimed at targeted groups like low-income communities have a potential of negatively affecting public health if an error of judgement is made at the policy level. The advancement of IAQ research in residential settings has driven studies on public health impacts of energy efficiency retrofit interventions.

The majority (32%) of the energy end-use consumption in residential buildings in the US happens for air conditioning and space heating [1]. In order to maximize the use of energy spent on home air-conditioning, home energy efficiency intervention programs guided by the federal Weatherization Assistance Program (WAP) focus on many strategies like equipment upgrades, window and door replacements, improving thermal insulation of the home shell structures and air-sealing of the building envelope to minimize the leakage of the conditioned air indoors.

Of the many techniques used to make residential buildings more energy efficient, the air-sealing activities are of primary importance for IAQ research because the air-sealing directly alters home ventilation rates. The air-sealing activities use techniques like window and door weather-stripping, window and door frame caulking, foam sealing of cracks and openings in the building envelope and sealing of the central air-handler ductwork. Reduction in home ventilation caused by these air-sealing activities have the potential to increase occupant exposure to higher concentrations of indoor air contaminants due to reduced pathways of exhausting to outdoors and less dilution of the contaminant concentrations with outdoor air.

Besides the potential degradation of IAQ caused by reduced home ventilation rates, additional factors associated with building characteristics like building age, building volume, condition and cleanliness of the central air-handler and its ductwork, operation of combustion appliances etc. in addition with the infiltration of outdoor air contaminants can also affect occupant exposure to indoor air contaminants, and hence, their health. Low-income households are considered more susceptible to the effects of exposure to air pollutants due to lower financial capacity to adapt to the rapidly changing environmental conditions [2].

Indoor air contaminants have been studied in relation to the ventilation rates and infiltration from outdoor air mostly in office settings and commercial buildings, however, there are limited data on this issue related to low-income households. Hence, there is a need for more research on the factors that can affect occupant health in low-income housing that can be systematically eradicated, providing both energy efficiency and better IAQ. A cross-sectional study of housing characteristics in relation to IAQ in low-income households can reveal a lot of important trends, especially if the sample size of the study is large.

The research work presented in this dissertation was hence undertaken as the Colorado Home Energy-Efficiency and Respiratory health (CHEER) study in the northern front range of Colorado, in which data were collected from a large sample size (with and initial target of 250 homes) representing the housing characteristics and building air leakage measurements. In its entirety, the CHEER study also had a component in which occupant respiratory health was studied with spirometry tests and health questionnaires in relation to building characteristics and building air leakage. This dissertation will only focus on the engineering aspects of the CHEER study.

1.1 Research objectives

There are two objectives of the research work presented in this dissertation:

1. To evaluate the effectiveness of the air-sealing energy efficiency retrofits implemented in low-income housing and identify IAQ indicators in homes that show associations with building airtightness.

2. To study the infiltration characteristics of outdoor air pollutants in low-income homes with direct air sampling measurements.

The two objectives are investigated in two separate chapters of this dissertation.

1.2 Hypothesis statements

Our hypotheses in the research study were as follows:

1. Air-sealing energy retrofits significantly reduce home ventilation rates and degrade IAQ.

2. Indoor environments of homes can provide significant protection against outdoor air pollution, even in low-income housing conditions.

Chapter 2

Literature Review

2.1 Climate change

The average temperature of the earth has risen by 1.4°F over the past 100 years and will continue to rise a further 2.5 to 10°F over the next century [3], causing large shifts in the climate. Since the past century, human activities have released increasing amounts of carbon dioxide (CO_2) and other greenhouse gases into the atmosphere. Activities that release CO_2 include burning coal to produce energy and deforestation. In the intermountain west, temperatures have increased by 2°F in the last 30 years [4]. Climate models predict that this region will warm by 5.5°F, and snowpack will decline by 21 to 25% by 2055 relative to a 1950-2000 baseline [5]. Climate change has been associated with increased natural and man-made disaster risk [6–8], international conflict [9], threat to global food security [10–12], hinderance to economic development [13–15] and large-scale biodiversity loss [16–18]. To reduce the serious impacts of climate change, humans must begin to reduce their emissions of greenhouse gases and use less energy.

2.2 Residential building energy use

The U.S. Energy Information Administration (EIA)'s Residential Energy Consumption Survey (RECS) estimated that in 2017, about 39% (or about 38 quadrillion British thermal units) of total U.S. energy consumption was consumed by the residential and commercial sectors. For residential buildings, space heating accounted for 15% of site energy consumption (Figure 2. 1). In Colorado in 2016, residential buildings accounted for 23.2% of the total energy consumption, 54% of which went to space heating, and only 1% went to air conditioning [19].

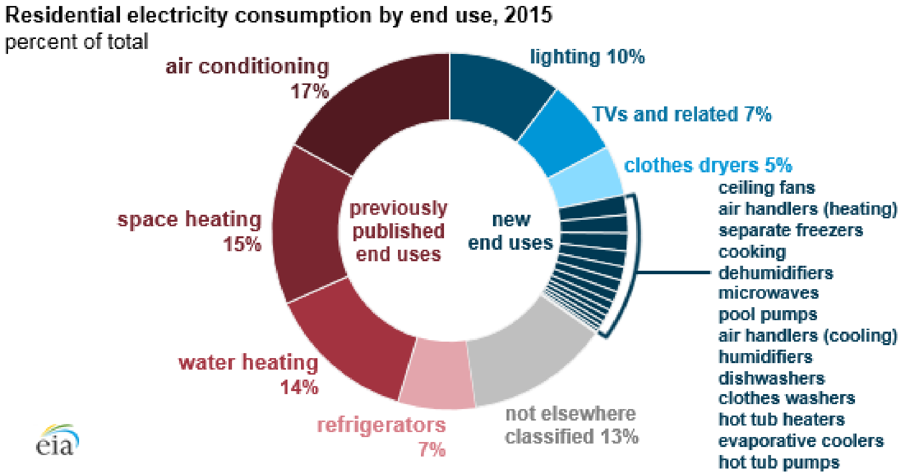

Figure 2. 1 Residential energy end-use pattern in the US. (Source: U.S. Energy Information Administration, Residential Energy Consumption Surveys) [19]

Besides direct conduction heat loss through the walls, much of this energy is lost through exfiltration, by escaping through unintentional openings in the homes, like cracks around doors and windows.

2.3 Home weatherization

Weather-proofing or *home energy retrofitting*, also called *weatherization*, refers to the practice of providing specific retrofits to an already built home to better protect the interior from the undesired effects of the external environment like sunlight, precipitation, wind etc., and also to improve the overall home energy consumption efficiency. More than 7 million US homes have received energy efficiency improvements since the start of the US DOE’s Weatherization

Assistance Program(WAP) created by the Congress in 1976 under Title IV of the Energy Conservation and Protection Act [20].

The purpose and scope of the of the program as currently stated in the Code of Federal Regulations (CFR) 10CRF 440.1 is “to increase the energy efficiency of dwellings owned or occupied by low-income persons, reduce their total residential energy expenditures, and improve their health and safety, especially low-income persons who are particularly vulnerable such as elderly, persons with disabilities, families with children, high residential energy users, and households with energy burden”. (Code of Federal Regulations, 2011) To be eligible for the program, households had to meet one of the two criteria: income at 150% of the federal poverty rate or income 60% or less of the state median income. The average cost to weatherize a unit was $4,695 [21].

The weatherization improvements include the following activities done to existing homes for upgrading the building energy performance [22]:

2.3.1 Mechanical measures:

- Clean, tune, repair or replace heating and/or cooling systems
- Install duct and heating pipe insulation
- Repair leaks in heating/cooling ducts
- Install programmable thermostats
- Repair/replace water heaters
- Install water heater tank insulation
- Insulate water heating pipes

- Install solar water heating systems

2.3.2 Building shell measures:

- Install insulation where needed
- Perform air-sealing
- Repair/replace windows/doors
- Install window film, awnings and solar screens
- Repair minor roof and wall leaks prior to attic or wall insulation

2.3.3 Health and safety measures:

- Perform heating system safety testing
- Perform combustion appliance safety testing
- Repair/replace vent systems to ensure combustion gas draft safely outside
- Install mechanical ventilation to ensure adequate indoor air quality
- Install smoke and carbon monoxide alarms when needed
- Evaluate mold/moisture hazards
- Perform incidental safety repairs when needed

2.3.4 Electric and water measures:

- Install efficient light sources
- Install low-flow showerheads
- Replace inefficient refrigerators with energy-efficient models

2.3.5 Client education activities:

- Educate potential household hazards such as carbon monoxide, mold and moisture, fire, indoor air pollutants, lead paint and radon
- Demonstrate the key functions of any new mechanical equipment or appliances
- Discuss the benefits of using energy-efficient products

The U.S. Department of Energy reports that weatherization improvements are done to approximately 35,000 homes every year through grants awarded to nearly 800 local agencies nationwide, which results in household savings of $283 or more on average, of which 18% corresponds to annual heating-consumption savings and 7% corresponds to annual electric consumption savings. Weatherization returns $2.78 in non-energy benefits for every $1.00 invested in the program. Over the years, the weatherization network and the private sector have established Guidelines for Home Energy Professionals including Standard Work Specifications for Home Energy Upgrades (SWS), and Home Energy Professional certifications and accreditation of energy-efficiency training programs [22].

Several field studies of weatherized homes have reported average reductions in air leakage of 13–40% [23] with a resulting average primary heating savings of 23% [24]. Homes that are weatherized under federal programs are currently required to have added ventilation if the home becomes too air tight (according to 2012 International Energy Conservation Code [25]). Unfortunately, tightening up a home can also have negative impacts on the IAQ within a home.

2.4 Indoor Air Quality Changes with home energy retrofits

Energy retrofits and efficiency improvement measures can have negative impacts on occupant health if not accompanied by IAQ protection measures. Air tightening the building shell prevents easy dilution of pollutants generated indoors (like carbon monoxide (CO), particulate matter (PM), and volatile organic compounds (VOCs) generated due to combustion appliances, secondhand smoke in residences with smokers, and hundreds of toxic chemicals continuously emitted by the building materials and consumer products inside the building) due to lower ventilation through infiltration and can worsen the IAQ over time [26].

Outdoor pollutant levels, indoor sources, natural infiltration or mechanical ventilation, pollutant transformation, and surface deposition determine indoor pollutant levels in homes [27]. Indoor sources produced by occupant behavior are episodic (cooking, showering) or intermittent (painting, pesticide use), whereas sources produced by the home construction are mainly continuous (emission from furnishing, materials, stored products). Home energy retrofits can improve IAQ by remediating existing hazards such as lead or radon, reducing air exchange with outdoor air lowering outdoor pollutant levels indoors, removing pollutant sources such as water leaks and unvented heaters, and by adding functional ventilation and/or filtration [27,28]. On the other hand, energy retrofits can worsen IAQ by disturbing legacy pollutants such as lead or asbestos, reducing ventilation leading to an increase in indoor pollutants, introducing new formaldehyde emitting construction materials, and failing to install mechanical venting when it is needed or installing unreliable systems.

Indoor air quality studies of weatherized residential buildings have shown that some pollutant levels increase, while others decrease. A recent study by Noris et al. (2013) [29]

conducted energy retrofits on 16 low-income multifamily apartments that were designed to save energy and improve IAQ. PM levels, CO_2, and VOCs generally improved whereas formaldehyde (HCHO) and nitrogen dioxide (NO_2) varied by building. Larger decreases in indoor sourced pollutants were realized with larger increases in ventilation rate and IAQ improved more in buildings with added mechanical ventilation (excluding particles). A modeling study of energy retrofit impacts on IAQ showed that air tightening by 40% (reducing leakage area from 12.5 to 7.5 ACH50[*]) worsened occupant exposures to all pollutants [30]. Most interventions reduced some pollutants and increased others. Kitchen exhaust had the broadest positive effects.

2.5 Impacts of weatherization on Lower-Income Communities

Low-income households also carry a larger burden for energy costs, typically spending 16.3% of their total annual income versus 3.5% for other households. Often, they must cut back on healthcare, medicine, groceries and childcare to pay their energy bills. Weatherization helps alleviate this burden through energy cost reduction [22].

Low-income communities are also disproportionately exposed to poor indoor and outdoor air quality as well as hazardous housing conditions [31–33]. Rates of asthma, including incidence and asthma morbidity are higher in low-income populations [34]. While low income populations may have the most to gain financially from reduced heating and cooling bills that energy retrofits can provide, they may also be most vulnerable to adverse health effects.

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[*] ACH50 = Air Changes per Hour at 50 Pa (result of blower door test)

2.6 Impacts of weatherization during wildfires

While tightening a home has the potential to increase pollutant levels indoors, particularly for those pollutants that originate indoors, it also may have a protective effect by keeping out unhealthy outdoor air pollution. A major concern in the western US is smoke from wildfires, which are a significant source of PM and CO. Climate change is expected to increase the frequency of wildfires and area burned [35–37]. Figure 2. 2 shows the increase in number of wildfires per decade in Colorado (CSFS 2014). Reducing exposure to wildfire PM will be protective for public health. Studies of health and wildfire incidence report significant adverse health outcomes. Künzli et al., (2006) [38] investigated self-reported symptoms of children ages 6–18 years old exposed to smoke from a large wildfire in Sothern California and found that symptoms were associated with self-reported level of exposure and PM_{10} concentrations (PM with diameters less than 10 μm). Statistically significant fire-related increases were observed in respiratory hospitalizations, for COPD and asthma [39]. During the Hayman fire in Colorado in the summer of 2002, self-reported adverse symptoms from COPD patients significantly increased on days with elevated $PM_{2.5}$ [40].

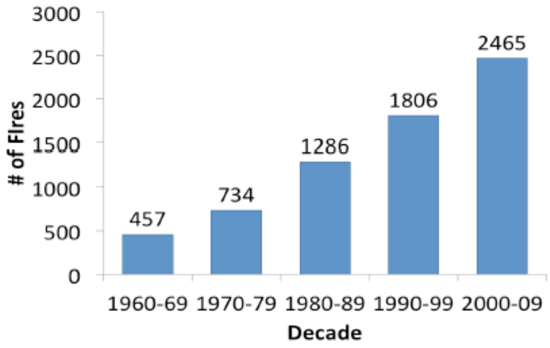
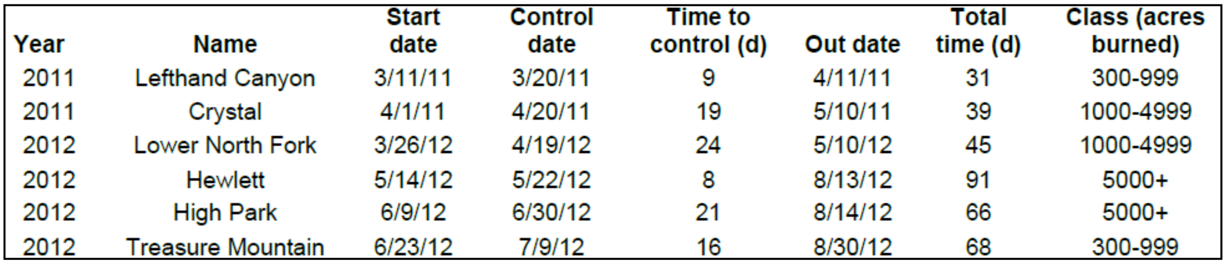


Figure 2. 2 Frequency of forest fires in Colorado [41]

In the last decade the average number of fires has risen to more than 2400 per year (Table 2. 1), with most of the fires in the warmer months. These fires routinely affect the air quality of Colorado front-range communities where ~80% of the state's households reside and where our study is being conducted. Larger and more frequent fire events have become more common in Colorado in the last few decades [42]. In 2012 (most recent data available), there were 1,498 fires and 246,000 acres burned in Colorado [43]. Over 5000 fires were started in the Rocky Mountains, burning over one million acres [44]. Table 2. 1 lists the front-range wildfires larger than 300 acres that burned longer than a week for the most recent two fire seasons for which data is available.

Table 2. 1 Recent wildfires in the front-range larger than 300 acres that burned more than 7 days [45]



Year	Name	Start date	Control date	Time to control (d)	Out date	Total time (d)	Class (acres burned)
2011	Lefthand Canyon	3/11/11	3/20/11	9	4/11/11	31	300-999
2011	Crystal	4/1/11	4/20/11	19	5/10/11	39	1000-4999
2012	Lower North Fork	3/26/12	4/19/12	24	5/10/12	45	1000-4999
2012	Hewlett	5/14/12	5/22/12	8	8/13/12	91	5000+
2012	High Park	6/9/12	6/30/12	21	8/14/12	66	5000+
2012	Treasure Mountain	6/23/12	7/9/12	16	8/30/12	68	300-999

The location of households relative to the fire may have important implications for both indoor and outdoor air quality measures. PM emissions from wildfires are carried over large distances increasing PM concentration in communities hundreds of miles from the event. Larger particles (greater than 10 µm) tend to settle closer to the source due to gravitational settling while fine particles (2.5 µm or less), which are of primary concern for IAQ and health, can be transported over long distances [46,47]. During wildfires, studies have shown that outdoor PM concentrations are significantly higher than indoor PM concentrations [48].

2.7 Ventilation and Infiltration measurements

Ventilation rate is an important quantitative indicator for IAQ. Ventilation rates are very often directly correlated with building-related respiratory health. It has been shown that lower ventilation rates can aggravate respiratory health problems related to poor indoor air quality arising from indoor tobacco smoke, dampness, textile wall paper and plasticizer containing surfaces [49]. Hence, leaky homes do have an advantage of having a cleaner indoor air due to the ventilation provided by naturally occurring infiltration. Therefore, there must be an optimum ventilation rate where energy expenditure in heating and cooling is minimized, while still ensuring an acceptable rate of removal of indoor air contaminants.

2.8 Blower door testing

Blower doors have been used to measure the air tightness and air leakage of building envelopes in thousands of single-family detached dwellings in the US. A blower door consists of a calibrated variable-speed fan that induces a range of airflows sufficient to pressurize and depressurize the building, a manometer to measure the pressure differential induced across the face of the fan and the building envelope, and a mounting system for a doorway. Blower door data is typically interpreted so that air leakage is expressed as “ACH50” (which is the air change induced by a 50 Pa pressure using a fan), as the “Effective Leakage Area,” or as the “Normalized Leakage” [50]. Leakage area is a good measure of weatherization impacts since the retrofits typically done are designed to reduce leakage/infiltration, which is how energy is typically lost in homes. Most homes that have been weatherized have a before and after blower door test to see how much the leakage was reduced.

2.9 Health Impacts Related to Weatherization

People spend a majority of their time indoors, and much of that time is at home. Health impacts of poor IAQ in homes depend on the type pollutant. The top four indoor air pollutants (IAPs) that have the highest chronic adverse health impact are particulate matter with diameters less than 2.5 microns ($PM_{2.5}$), secondhand smoke, radon (smokers), and formaldehyde [51]. Indoor air pollution sources and occupant behavior have the potential to increase IAP exposure levels when a home envelope becomes tighter. Exposure to pollutants originating outdoors would decrease, on the other hand.

Health effects studies which have mostly been done recently on multifamily residential buildings have shown varying outcomes. Some early studies related to monitoring the respiratory health of occupants in buildings concluded that building air tightness and inadequate air exchange in buildings could be directly correlated with negative health effects ranging from psychological discomfort to sick building syndrome (SBS) [52–55]. Engvall et al. (2003) [56] concluded that for reconstruction of older multi-family houses, major reconstruction of the interior (with introduction of new building materials and paints) and multiple sealing measures of buildings were associated with an increase in symptoms related to ocular, nasal, dermal and respiratory symptoms. When energy retrofits contain large number of plastic components, it may worsen asthma conditions. A study [57] shows that certain plasticizers used in building materials (like DEHP) can exist in aerosol or particulate form which can worsen asthma.

More recent studies, however, have shown positive health impacts of weatherization on occupant health. Wilson et al. (2013) [54] showed that self-reported general health of the residents improved after home energy retrofits including improvement in sinusitis, hypertension and thermal comfort conditions, but concluded that more research was needed to ascertain about asthma-related outcomes. Breysse et al. (2011) [58] reported on a green renovation of three multifamily affordable housing buildings that resulted in adults reporting significant improvement in overall, asthma, and significant improvement in non-asthma respiratory health along with a decline in radon levels and a dramatic decline in home energy use.

Chapter 3

Impact of Energy Efficiency Retrofits on Air Tightness and Indoor Air Quality Indicators in Low-Income Homes

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3.1 Abstract

Home ventilation is an important predictor of indoor air quality (IAQ). It is unclear how the reduction in home ventilation caused by energy retrofits made to low-income housing affects indoor air quality. We studied 226 low-income households as a part of the Colorado Home Energy Efficiency and Respiratory Health (CHEER) study to investigate the relation between energy efficiency retrofits (EERs) specific to air-sealing of residential building envelopes, annual average air exchange rates (AAER), and indoor air quality in low-income households in Colorado, USA. Blower door tests quantified the leakage area in each home, which was used to estimate the AAER. Walkthrough inspections were used to record observations of air-sealing retrofits in building envelopes and indirect indicators of poor IAQ in the homes like visible mold or stains, vapor condensation on windows, dampness, and perceived IAQ. Results showed that building characteristics like age and volume affected AAER more significantly than air-sealing EERs. Among the air-sealing EERs, homes with the air-handler ductwork sealed and windows weather-stripped were found to have significantly lower AAER compared to the homes without these features. Although median AAER or EER homes were 16.7% lower than non-EER homes, some homes with EERs had higher AAERs than conventional homes due to poor quality of EER work. Mold growth, wall stains, notably higher level of dust and unacceptable odor levels were reported mostly in homes with up to 48% higher AAER showing that leakier homes do not necessarily have better IAQ.

3.2 Introduction

Building energy efficiency retrofits (EERs) refer to upgrades applied to an existing building to make it more energy efficient. Such upgrades are often performed during the weatherization process performed by contractors and homeowners. Besides the wide variety of energy upgrade activities done to building systems and appliances, EERs also focus on building envelope air-sealing activities aimed to reduce air exchange, and hence, the consumption of energy needed for indoor temperature control. The air-sealing activities related to EERs include door and window weather-stripping, caulking of door and window frames, foam sealing of cracks in the building envelope, caulking around plumbing and electrical and combustion appliance exhaust conduit penetrations through roofs and walls, and, sealing of leakage points in heating system ductwork [59].

Residential building EER programs in the US have been subsidized through the US Department of Energy (DOE)’s Weatherization Assistance Program (WAP) since 1976 to increase energy savings in low-income communities. The DOE provides weatherization services to approximately 35,000 homes every year – a total of seven million homes have been weatherized through the spring of 2018. DOE reports that weatherized single-family households experience an average of $283 or more in annual energy savings [59].

Air-sealing is aimed at reducing air leakage, or conversely, increasing building air-tightness. A minimum level of ventilation or leakiness is still necessary to maintain a healthy and safe indoor air quality for the occupants. Most homes are ventilated with natural ventilation practices (open windows and doors) or infiltration. Infiltration is ventilation through unintended openings such as cracks in the building structure. Ventilating buildings with outdoor air dilutes and removes pollutants emitted from indoor sources. Therefore, lower ventilation rates may result in elevated exposures from accumulation of pollutants generated indoors and cause adverse health effects, such as exacerbation of asthma symptoms and other respiratory diseases, and sick building syndrome (SBS) symptoms [60–65]. The ASHRAE 62.2 Standard provides guidelines for achieving ventilation and acceptable indoor air quality in residences and adding continuous mechanical ventilation in homes with insufficient natural ventilation [66].

While the aim of reduced energy consumption via home EER interventions may be well intentioned, the air-sealing activities can introduce a suite of indoor air quality (IAQ) problems, especially if adequate ventilation is impeded by the retrofits. The characteristics of a typical home are inter-related so that changing one component directly or indirectly changes the operation of other components as well, which can influence indoor air pollutant exposures in the home. Tighter homes more readily depressurize when exhaust equipment is operated, making combustion appliances more prone to backdraft or spillage, and current codes and standards related to combustion appliance installations have failed to provide adequate information on assessing back-drafting or spillage potential [67]. Very low air exchange rates in buildings have also been associated with elevated indoor radon concentrations [68].

Previous studies have investigated the impacts of EERs on IAQ [69–71]. Energy retrofits can alter exposures to some indoor pollutants and the use of new building materials can introduce a wide variety of toxic chemicals indoors following the retrofits [71–74]. A study conducted on 514 homes across the US with indoor air contaminant measurements pre- and post-weatherization by WAPs concluded that weatherization caused a small but statistically significant increase in radon and humidity, dependent on season [71]. Another study, conducted in Ireland in 15 three-bedroom semi-detached cooperative social dwellings before and after energy upgrades, reported a significant increase in indoor concentrations of CO_2, TVOC, and $PM_{2.5}$ [75]. A study conducted in

North Carolina in nine homes also found that homes had above-recommended levels of TVOC and formaldehyde after weatherization [76].

While most studies on IAQ impacts of EERs focus on indoor concentrations of specific pollutants, there are limited data on how the air-sealing activities individually affect building air tightness in low-income households, and the potential impacts that building air exchange rates could have on different IAQ indicators. This paper first describes the household characteristics of the study population in relation to building airtightness and IAQ, and then analyzes the role of air-sealing EERs on building airtightness. Five air-sealing activities are separately considered for this study which include: (1) door weather stripping, (2) window weather stripping, (3) door- and window-frame caulking from the building exterior, (4) foam-sealing of cracks and openings on the building envelope, and (5) sealing of air handler ductwork. Our null hypothesis is that homes with air-sealing EERs have lower AAER and the homes with lower AAER will have more significant IAQ problems.

3.3 Methods

3.3.1 Study Recruitment

Participants were enrolled into the study through letters mailed to the homes that met the low-income criteria set by the Low-income Energy Assistance Program (LEAP) in the state of Colorado. This mailing was accomplished through a partnership with Colorado Xcel Energy, Boulder Housing Partners, and Loveland Habitat for Humanity. Each household was given a $25 gift card to incentivize participation. To be eligible to be enrolled in the CHEER study, each home had to meet the inclusion criteria, which included: each building had to be a single-family home, duplex or townhome with no direct air exchange vents in between each unit, enabling independent air conditioning of each unit; the households were required to be defined as low-income by the participating agency (annual income below 80 percent of the median income of the area); and the households had to be nonsmoking. Upon enrollment a team of three persons conducted a home visit in each home that lasted up to two hours. The study protocols were approved and authorized by the University of Colorado Boulder Institutional Review Board (Protocol 14-0734).

3.3.2 Building airtightness

Each home was tested for airtightness using a computer automated multi-point depressurization blower door test (Minneapolis Model 3 Blower Door with DG-700 digital pressure gauge, Minneapolis MN) using TECTITE 4.0 software for test automation. The test protocol [77] used for the blower door tests required homes to be depressurized sequentially from -50 Pa to -15 Pa with decrements of 5 Pa and the corresponding volumetric fan airflow rates measured in cubic feet per minutes (CFM), which resulted in the characteristic leakage curve (Eq.3.1) for each test. Air tightness of each building was parameterized as air changes per hour at a pressure of -50 Pa with respect to outdoors (ACH50) along with other parameters of the characteristic leakage curve.

$$Q = C(\Delta P)^n \tag{3.1}$$

where Q is the fan flow rate (CFM), C is the air leakage coefficient (unitless), ΔP is the indoor-outdoor pressure differential (Pa), and n is the pressure exponent (unitless).

The annual average air exchange rate (AAER) was then estimated using the Lawrence Berkeley National Laboratory (LBNL) infiltration model [78] that is built into the TECTITE 4.0 software [79]. The LBNL model considers the climate of the location, number of bedrooms, building dimensions, indoor and outdoor temperatures, and wind shielding category along with the leakage curve parameters to predict AAER. The AAERs were adjusted if the house had a continuously running mechanical ventilation (MV) system per the method from Palmiter and Bond [80], [81]. Eleven homes in our study had MV systems and their AAERs were adjusted. Eight of the homes had heat recovery ventilation (HRV) systems which were operated not continuously, but intermittently with timer switches and AAER calculations could not be made for these homes with the technique described above but were omitted from the analyzed dataset.

AAER was treated as the main independent variable representing building airtightness as it also considers the effects of mechanical ventilation. Corresponding ACH50 values are also discussed where relevant for comparability with other studies. The measurement of building volumes used for the blower door tests excluded attached garages, attic spaces and porches that were outside the conditioned zones.

3.3.3 Evaluation of Energy Efficiency Retrofits

Household walkthrough inspections were conducted in each home to note the characteristics of each building. Based on the EER characteristics observed, homes were categorized into three building types: (1) Homes with observed EER changes to their structure (EER homes); homes with no special energy efficiency features (non-EER homes) and built-green homes (BG homes). Most of the EER changes were implemented by the State of Colorado’s WAP. The BG home energy efficiency improvements were subsidized as affordable housing, either through city housing authorities or Habitat for Humanity, and had distinct characteristics compared to the non-EER homes like very airtight construction; significantly higher degree of attic, wall cavity, and crawlspace insulation; and high efficiency windows, heating equipment, and appliances.

Based on the observations made during the walkthrough surveys, we created a scoring scheme termed an EER-score, denoting the number of observed air-sealing related EERs in the homes. The EER-score was determined as a cumulative score of a total of five points, one point each given to an air-sealing activity visible from the living spaces, which were: (1) all doors having weather stripping, (2) all windows having weather stripping, (3) all exterior door/window frames caulked, (4) foam sealing present in cracks and openings, and (5) air handler ductwork sealing job performed.

3.3.4 Indicators of IAQ

Observations that indicated poor IAQ conditions were recorded during the walkthrough surveys like the presence of mold or stains, visible dust on surfaces, dampness on walls, vapor condensation on window pane interior, dead bugs, spider webs, and presence of noticeable drafts. The supplement section provides the survey questionnaires.

To assess the indoor dust level in each room of each home, an ordinal 5-point dust score ranging from 0 (no dust) to 5 (high dust) was used by each surveyor. To minimize the variability in data across different surveyors, each surveyor was trained with the same training materials before starting the home visits. Median values of the dust score were then calculated as the representative value of each home and was named as the median indoor dust score (MIDS). The MIDS were then compared to a median value of the range (=2.5) to categorize homes as having a "high" or "low" dust level indoors. Since the infiltration of outdoor dust could potentially be one of the significant sources of the indoor dust, the association between MIDS and outdoor dust concentrations were investigated indirectly based on the distance of each home from the closest major road because past studies have shown that outdoor dust (particulate matter) concentrations in urban areas are significantly higher up to 200 meters from a major road [82]. The closest major road with annual average daily traffic (AADT) of at least 10,000 vehicles was taken as the reference road based on previous research [83,84].

Data were also collected on perceived indoor air quality (PIAQ) surveys that we devised. The PIAQ questionnaires were answered by the walkthrough surveyor at a single central location in the home. To reduce the bias in data introduced by subjective adaptability of perception, walkthrough surveyors were trained to only answer the PIAQ questions based on immediate entrance to the house and not the perception at a later point in time. The three yes/no PIAQ questions were: "Does the air in the house feel fresh?", "Is there a significant room-to-room variation in the temperature?" and, "Is the level of odor acceptable?". A positive response in each case was denoted by 1 and a negative response by 0.

3.3.5 Data Analysis

Data were analyzed using the R programming language (Version 3.4.4). Dummy variables were used when grouping the data into different categories. For continuous variables, first the sample distributions were investigated using histogram plots. If the data showed distinct visual features like that of a normal or lognormal distribution, an Anderson-Darling (A-D) test was used in addition to quantile-quantile (Q-Q) plots to confirm the normal distribution of the data (or normality of log-transformed data). If the A-D test failed to reject the null hypothesis of the normality assumption ($p>0.05$) in the sample distribution, a two-sample unpaired t-test with unequal variances was used to test for statistical difference in means between two groups and one-way analysis of variance (ANOVA) for more than two groups (tests performed on log-transformed data). As per the need, Tukey's honestly significant difference (Tukey HSD) post-hoc test was conducted after ANOVA to investigate pair-wise significance in the difference of means between groups.

If a significant deviation ($p<0.05$) from the normality assumption was reported by the A-D test, the non-parametric Kruskal-Wallis (K-W) test was used for differences in medians. Linear regression analyses were also performed to investigate the strength and statistical significance of association between the continuous variables of interest. Correlation between variables are reported as Pearson's correlation coefficient (r). Level of significance of 5% ($p=0.05$) was used in all the statistical tests and a p-value of >0.05 to 0.1 was defined as marginal significance.

Statistical multilinear models were used to account for the variation in AAER among the households due to potentially relevant parameters collected from the walkthrough surveys, and the location and age of the homes. The variables were first tested using ANOVAs and simple regression models and then selected variables were used in the multilinear models to predict ln(AAER) since AAER was found to be lognormally distributed.

Model 1 predicted AAER using only the EER-scores:

$$\ln(AAER) = \beta_o + \sum_{i=1}^{5} \beta_i A_i + \varepsilon \tag{3.2}$$

where A_i represents each individual EER-score, β_0 is the intercept of the regression, β_i 's represent the coefficients of each predictor terms and $\boldsymbol{\varepsilon}$ represents the residual error term.

Model 2 was constructed to evaluate the relative effects on AAER introduced by other significant predictors like building volume and building age:

$$\ln(AAER) = \beta_o + \sum_{i=1}^{5} \beta_i A_i + \beta_6 Y + \beta_7 V + \beta_8 V * Y + \varepsilon \tag{3.3}$$

where the first two terms are the same as in Model 1, Y represents the age of the building in years and V represents the building volume in cubic feet. β_6, β_7 and β_8 are the regression coefficients of the age, volume and age-volume interaction terms, respectively.

3.4 Results and Discussion

3.4.1 Enrolled study homes

A total of 226 homes were enrolled in the Colorado Home Energy Efficiency and Respiratory Health (CHEER) study from low-income households located in the cities of Denver, Aurora, Boulder, Loveland, and Fort Collins. The study took place from October 15, 2015 to April 15, 2017. Because of the data unavailability in some homes, data from 216 homes are presented in this paper.

Figure 3. 1 shows the spatial distribution of homes recruited for the CHEER study, which ranged from 1600 m to 1770 m above sea level in the International Energy Conservation Code (IECC) climate zone 5 dry (B) region [85]. The EER and non-EER homes were evenly distributed across all census tracts. Built Green homes were located only in the Boulder and Loveland areas.

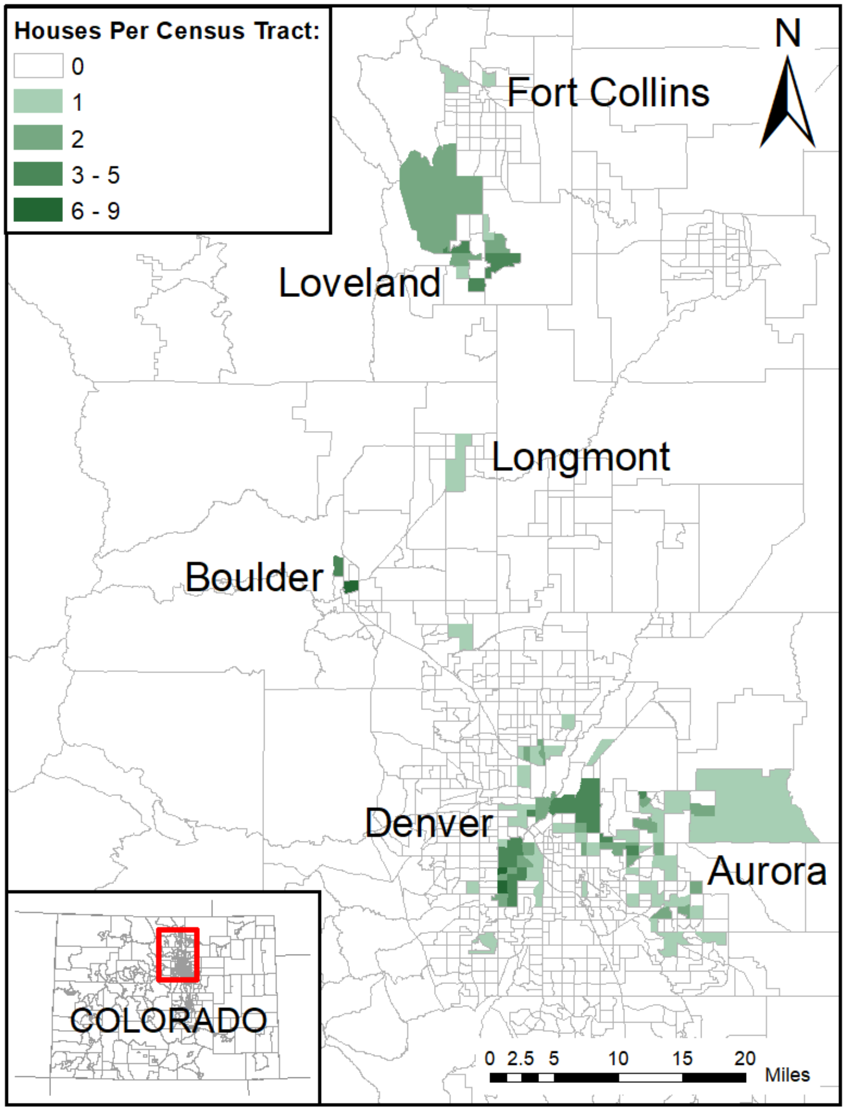


Figure 3. 1 Map of the study region showing number of homes enrolled per census tract.

3.4.2 Household characteristics

Table 3. 1 summarizes the number (and percentage of the total sample size) of homes based on various categories of building characteristics noted during the walkthrough surveys.

Table 3. 1 Summary of the number of CHEER study home characteristics

Categorizations	N (% of total)
Home counts	
Total number of home visits	226
Homes with usable blower door test data[*]	218
Homes with both walkthrough and blower door data available[†]	216 (100)
Homes with air-sealing EERs	
All doors weather stripped	156 (72.2)
All windows weather stripped	116 (53.7)
Door/Window frames caulked	123 (56.9)
Foam sealing of cracks/openings	37 (17.1)
Furnace ductwork sealed	70 (32.4)
None present in the house	27 (12.5)
Location	
Aurora	44 (20.4)
Boulder/Ft. Collins	31 (14.3)
West Denver	81 (37.5)
Central/North Denver	60 (27.8)
EER status	
BG	7 (3.2)
EER	114 (52.8)
Non-EER	95 (44.0)
Building age	
Built before 1976	146 (67.6)
Built after 1976	50 (23.1)
Missing age data	20 (9.3)
Housing type	
Single family	182 (84.2)
Duplex/Townhouse	34 (15.7)
Number of stories	
1-story	164 (76.0)
1.5-story (split level)	2 (0.9)
2-story	48 (22.2)
3-story	2 (0.9)
Distance from the closest major road [a]	
<200m	99 (45.8)
>200m	113 (52.3)
No data available	2 (0.9)
Dedicated ventilation systems	
Continuous MV installed	11 (5.1)
Radon mitigation system installed	10 (4.6)
Heating sources	
Electric baseboard heating	3 (1.4)
Gas furnace (forced air)	197 (91.2)
Gas boiler (baseboard heating)	6 (2.8)
Gas fireplace	31 (14.3)
Wood fireplace	38 (17.6)
Wood stove (wood burning)	4 (1.9)
Wood stove (gas burning)	3 (1.4)
Appliances	
Gas stove	81 (37.5)
Electric stove	135 (62.5)
Gas water heater	160 (74.0)
Electric water heater	10 (4.6)
Gas dryer	21 (9.7)
Electric dryer	183 (84.7)
Stove hood type	
Outdoor exhausting	53 (24.5)
Recirculating	99 (45.8)
Stove hood absent	81 (37.5)
Homes with potential IAQ problems	
Window condensation observed	22 (10.2)
Mold growth visible on interior walls or ceiling	69 (31.9)
Stains visible on interior walls or ceiling (other than mold)	124 (57.4)
Dampness on walls/floor[‡]	46 (21.3)
Visible leaky pipes	19 (8.8)
Used candles present	100 (46.3)
High level of dust indoors[**]	30 (13.9)
PIAQ survey results	
Air perceived as "not fresh"	83 (38.4)
Odor perceived as "not acceptable"	31 (14.3)
High degree of noticeable room-to-room variation in temperature	38 (17.6)

EER= Energy Efficiency Retrofit; HRV=Heat Recovery Ventilation; MV= Mechanical Ventilation

[a] Annual average daily traffic ≥ 10,000

[*] Blower door test could not be done in few homes due to safety reasons

[†] Two homes had missing walkthrough survey data. Data analysis were performed for only the homes with both blower door data and walkthrough data available.

[‡] Felt by the sense of touch by the surveyor

[**] Evaluated with the 5-point dust scale mentioned in methods section

Out of the 216 homes for which data were analyzed, 52.8% of the homes were constructed before 1976, the year when WAP came into effect. Most homes (84.2%) were detached single family buildings and were single-story (76%), and 45.8% of the homes were located less than 200 m from a major road.

In terms of air-sealing AAERs observed in homes, the most common was door weather-stripping (72%) and the rarest was foam sealing of cracks and openings (17.1%). Very few homes (12.5%) had none of the air-sealing EERs visible from living spaces in the home. Many retrofits for energy efficiency were not observable by walkthrough and include insulation blown into wall cavities and attics, caulking of attic floor level, and foam sealing of inaccessible crawl spaces. We were unable to obtain information about all retrofits done in homes serviced by WAP contractors.

PIAQ survey results showed that 38.4% homes had air that was perceived by the surveyor as “not fresh”, 14.3% homes had unacceptable odor level and 17.6% homes had notable thermal discomfort between rooms. A past study found that thermal and aural qualities in the indoor environment were deemed the most important contributors to the occupants’ acceptance of the overall indoor environmental quality (IEQ), whereas indoor air quality was considered the least important [86], and people tend to deem an IEQ unacceptable due to thermal discomfort, but not due to elevation in indoor pollutants like carbon dioxide. Given a small fraction of the total number of homes with notable temperature variation across different rooms, it can be said that occupants most low-income homes that we studied in the CHEER study did not have significant thermal discomfort in their homes and found the indoor environments to be acceptable despite our surveyors finding a fraction of the homes to have perceivable IAQ problems.

Visual cues observed during the walkthrough surveys indicated that a significant portion the homes (between 8.8% to 57%) had some form of an IAQ problem. 57.4% of the homes had stains somewhere on the walls, ceiling, or floor that was visible from the living space. 32% of the homes also had mold growth that was directly visible from the living space. About one-fifth of the homes had dampness on the walls or floors and 10.2% of the homes had condensation on the windows, both indicating potential mold problems either in the present or the future. Almost half of the homes also had burnt candles indicating sources of indoor fine particulate matter and carbon monoxide, which are known to be harmful for respiratory health. Most homes had either a recirculating type or no stove hood and only 24.5 % of the homes had outdoor exhaust stove hoods. The absence of exhaust-type stove hoods is particularly dangerous for occupant health in homes with gas stoves. Yet, 34 homes (15.7%) had gas stoves with no stove hood at all, and 59 homes (27%) had gas stoves with no exhaust-type stove hood.

3.4.3 Participant demographics

The CHEER study homes were occupied by 302 inhabitants. Majority of the occupants lived in the West Denver region (n=112, 37% of total), were females (n=203, 67%), non-Hispanic Whites (n=123, 41%), and were 50 years or older (n=182, 60%). A summary of the occupancy of CHEER study occupant demographics is given in the supplement section (Table S3).

3.4.4 Building airtightness

Blower door tests were conducted to measure the air-tightness of the study homes. The blower door test results quantified as air changes per hour at an indoor pressure of -50 Pa (ACH50 [hr^{-1}]), were found to be log-normally distributed. Like ACH50, AAER [hr^{-1}] was also found to be log-normally distributed. Hence, log-transformed ACH50 and AAER values were used in the statistical tests.

A simple linear regression analysis between ACH50 and AAER revealed that a strong correlation existed between the two variables (r=0.96) with an R^2 of 0.92 (F (1, 214) =2547, p<0.000). This is not surprising since the LBNL model used to estimate the AAER had the leakage area estimated from the blower door tests as one of its main inputs. The average ACH50 for the CHEER study homes was 11.9 hr^{-1} (standard deviation of 6.7 hr^{-1}) which is comparatively lower compared to the average ACH50 value of 29.7 hr^{-1} measured in 1998 across the US [87], yet significantly higher compared to the 2012 International Energy Conservation Code (IECC)'s requirement of 3 hr^{-1} for new construction based on the climate of Colorado [88].

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) standard 119 [89] also uses *normalized leakage* as a metric for building leakage (and consequently air-tightness), where normalized leakage (NL) is calculated as:

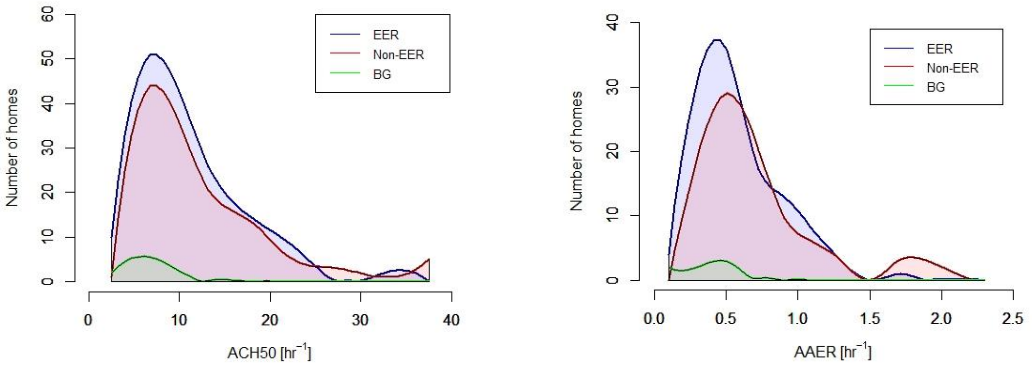
$$NL = 1000\frac{ELA}{A_f}\left(\frac{H}{H_o}\right)^{0.3} \tag{3.4}$$

where, ELA is the effective leakage area measured from blower door test (m^2), A_f is the floor area of the building (m^2), H is the building height (m) and H_o is the reference height of a single story (2.5 m).

The average normalized leakage for our study homes was 0.72, which was 17% lower compared to the 1998 estimate for Colorado of 0.87 [87] but 12.5% higher the average value of 0.64 calculated from a database comprising of more than 70,000 homes in the U.S. [90]. We conclude that the homes in our study were quite leaky especially by region (West Denver was much leakier) despite many homes having undergone weatherization efforts – a finding consistent with other studies [87].

While conducting a blower door test, the negative pressure inside the house created by the blower door fan can close the exhaust vent damper connected to the MV system. The blower door test will hence report ACH50 values neglecting the MV system. In the absence of this negative pressure, however, the MV system exhaust can push open the damper, and create a greater airflow on average than that reported by the blower door test. The modification of AAER based on this effect was thus necessary. Significant linear regressions were also calculated between ln(AAER) and building volume [ft^3] (F (1,214) =102.9, $p<0.000$, $R^2=0.32$, $r=-0.57$), and between ln(AAER) and building age [years] (F (1,192) =45.48, $p<0.000$, $R^2=0.19$, $r=0.44$). This result is also consistent with past studies [90–92].

Although statistically different means in ACH50 as well as AAER were observed for the different building types by EER status and median AAER or EER homes were 16.7% lower than non-EER homes (Table 3. 2), the overall distribution pattern of EER and non-EER homes were not significantly different from each other (Figure 3. 2).



(a) (b)

Figure 3. 2 Distribution of building air-tightness across building types (a) ACH50 (b) AAER. Smoothed distributions were generated by connecting the histogram mid-points with spline curves.

Table 3. 2 Summary of AAER according to different building characteristics

	AAER [hr^{-1}]			
Categories	n	Median	Range	p-value[*]
Location				
Aurora	44	0.48	0.22-2.2	<0.000
Boulder/Ft. Collins	31	0.47	0.10-1.9	
West Denver	81	0.69	0.29-2.0	
Central/North Denver	60	0.50	0.16-1.9	
EER status				
BG	7	0.33	0.10-0.57	0.0002
EER	114	0.50	0.16-1.7	
Non-EER	95	0.60	0.25-2.2	
Building Age				
Built before 1976	146	0.57	0.16-2.2	<0.000
Built after 1976	50	0.44	0.10-1.1	
Housing type				
Single family	182	0.51	0.10-2.0	0.032
Duplex/Townhouse	34	0.67	0.17-2.2	
Number of stories				
1-story	164	0.53	0.10-2.2	0.72
1.5-story (split level)	2	0.60	0.27-0.93	
2-story	48	0.57	0.32-1.66	
3-story	2	0.47	0.22-0.72	
Proximity to the closest major road [a]				
<200m	99	0.55	0.22-2.2	0.15
>200m	113	0.55	0.10-1.8	

[*] ANOVA at $\alpha=0.05$

[a] Major road defined as annual average daily traffic volume of at least 10,000 vehicles

AAER was found to vary significantly by location (ANOVA, F (3,212) =7.78, $p<0.000$). Running a Tukey HSD post-hoc test showed that the mean (± standard deviation) AAER of West Denver homes (0.74 ± 0.36 hr^{-1}) was significantly higher (+54%) than Boulder/Ft. Collins homes (0.48 ± 0.22 hr^{-1}, $p<0.000$), 23% higher than the Central/North Denver homes (0.60 ± 0.34 hr^{-1}, p = 0.012), and marginally significantly higher (+25%) than Aurora homes (mean = 0.59 ± 0.34 hr^{-1}, p=0.065). Between other regions, mean AAER values were not significantly different.

Median AAER of single family homes were found to be 24% less than duplexes or townhomes. Single family homes have all the exterior walls of the building available for direct air exchange with the surroundings, which is not the case in duplexes and townhomes. Intuitively, single family homes should have had a higher AAER in that sense. However, it was found that single family homes also had a median volume of 287 m^3, which was 35% higher than the median volume of duplexes/townhomes, which was 213 m^3. Since we found an inverse relation between AAER and building volume, this explains the variation in median AAER between the two categories. In addition, hidden passage ways (through attics, crawlspaces and wall cavities, for example) could have been present in duplexes and townhomes that could have affected the blower door test measurements.

Building age also significantly impacted AAER and ACH50 (data not shown). This result has been reported by Sherman and Dickerhoff, who report that homes prior to 1980 were on average leakier and showed a clear increase in leakage with increasing age [87]. According to Chan et al. (2005) [93] who found similar results, some reasons why newer dwellings might tend to be tighter than older ones include improved materials (e.g. weather-stripped windows), better building techniques (e.g. air barriers) and lesser degrees of age-induced deterioration (e.g. settling of foundation).

3.4.5 EER-scores

A statistically significant negative relationship was found between EER-score and AAER (Figure 3. 3 (a)). AAER distributions had significantly higher medians in most cases for EER scores of zero, compared to the median AAERs in non-zero EER categories. The changes in AAER when the EER scores increased sequentially from one to five, however, were not monotonic in nature, and depended on the location of the homes (Figure 3. 3 (b)).

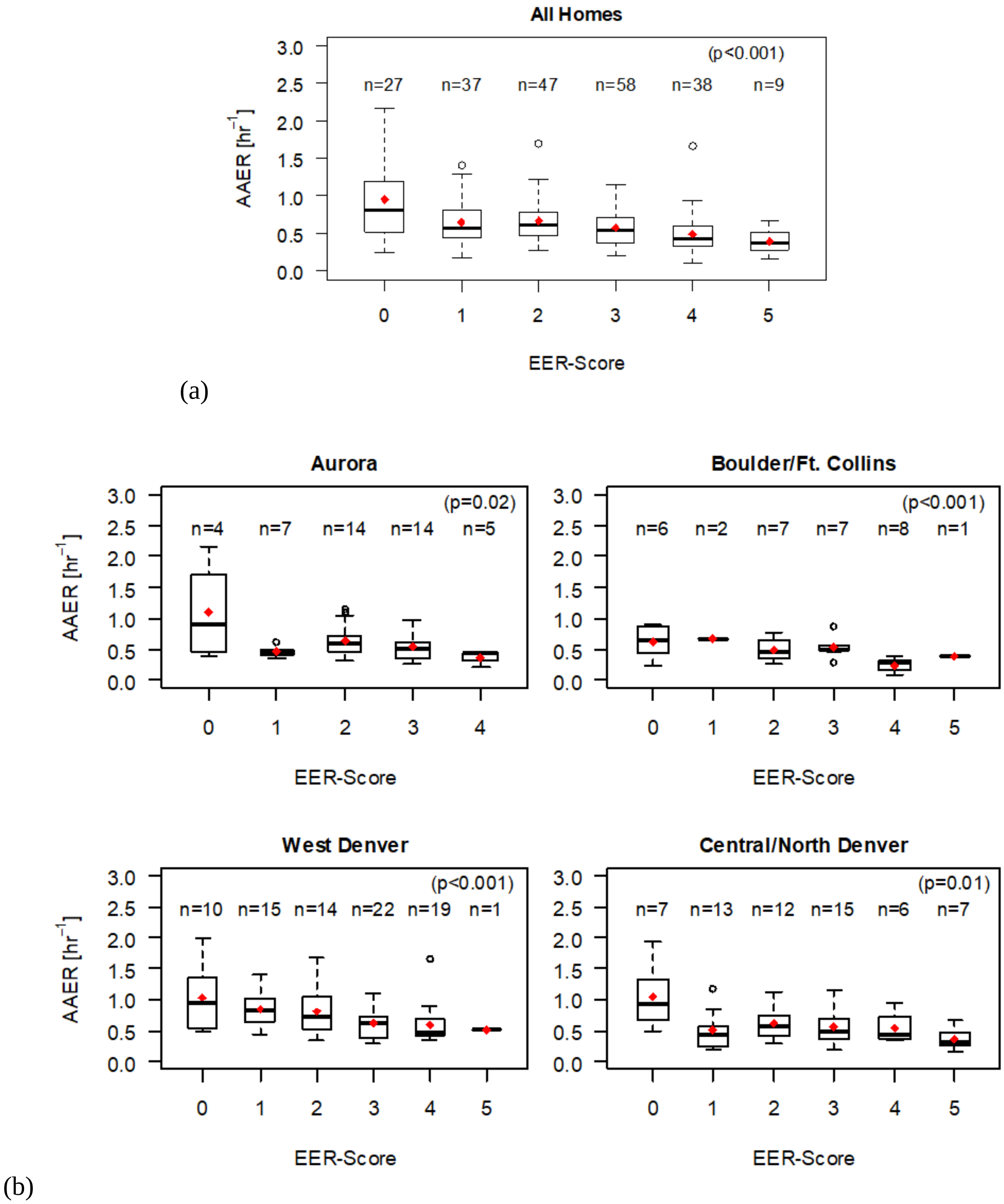


Figure 3. 3 Box and whisker plots showing AAER distributions in (a) all homes and (b) homes in different locations, by cumulative EER-scores for different air-sealing activities. Red diamond dots indicate sample means and p-values in parentheses indicate significance of differences in means between the groups (ANOVA, p<0.001).

A multilinear regression was used to predict ln(AAER) using the different EER-score components (Model 1, Eq. (3.2)). A significant regression was calculated (F (5,210) = 9.03, p<0.000) with normally distributed residuals. AAER was significantly lower in the homes where all the windows were weather-stripped, and the air-handler ductwork was sealed. No significant differences in AAER were seen in homes with other air-sealing EERs other than these two (Table 3. 3). A study of 91 homes in Florida reported that 12-14% of house leaks were in the duct system and duct repairs improved building tightness by decreasing the ACH50 from an average of 12 to 11, saving an annual average of $200 in energy costs per home [94]. A previous study of retrofit impacts reported that the average retrofit reduced leakage by 25% [87]. We did not have the opportunity to measure air tightness before any of our homes had been retrofitted, as this was not part of the study design.

Table 3. 3 Results of multiple regression predicting AAER with five-different air-sealing EERs according to Model 1 (Eq. (3.2)).

Predictors	Coefficients (β)	s.e.*	p-value
Intercept	-0.278	0.065	0.000
All door weather-stripping (A_1)	-0.130	0.081	0.110
All window weather-stripping (A_2)	**-0.241**	0.075	0.002
Door/Window frame caulking (A_3)	0.021	0.078	0.784
Foam sealing of cracks/openings (A_4)	-0.055	0.085	0.518
Air handler ductwork sealing (A_5)	**-0.278**	0.070	0.000

* Standard error

N=216, Adjusted $R^2 = 0.157$

To investigate the combined effects of the air-sealing EERs and other significant predictors like building age and building volume, another multilinear regression was calculated using Model 2 (Eq. 3.3). The age information related to some buildings was not available, hence Model 2 was run on a smaller sample size of n=194, with two homes built in the same year.

Table 3. 4 Multilinear regression statistics for model 2 (Eq. (3.3)) for predicting AAER with air-sealing EERs along with building volume and building age.

Predictors	Coefficients (β)	s.e.[*]	p-value
Intercept	-0.660	0.167	0.000
All door weather-stripping (A_1)	-0.007	0.069	0.918
All window weather-stripping (A_2)	-0.100	0.063	0.114
Door/Window frame caulking (A_3)	-0.004	0.064	0.951
Foam sealing of cracks/openings (A_4)	-0.050	0.070	0.472
Air handler ductwork sealing (A_5)	-0.111	0.061	0.073
Building volume (V)	-1.65E-05	1.13E-05	0.148
Building age[†] (Y)	**0.012**	0.002	0.000
Interaction term (V*Y)	**-6.55E-07**	2.01E-07	0.001

[*] Standard error

[†] w.r.t. the year 2018

N=194, Adjusted $R^2 = 0.467$

Table 3. 4 shows that the contribution from air-sealing EERs on AAER were insignificant compared to the contributions from building age and building volume. However, air handler ductwork sealing was found to be marginally significant and was the most significant contributor in AAER reduction among all the air-sealing EERs considered. Our result is in agreement with a past study which had also found that floor area and year built were the two most significant predictors of the building envelope leakage area [93].

A large sample size and robust methods like the use of blower door test was helpful to identify a lot of statistically significant associations between various building categories and AAER. However, there were certain limitations inherently present due to the study design. Accurate records of furnace, water heater, door, and window replacements by the WAP contractors were not available. Hence, a detailed scenario related to the effectiveness of EERs was not assessed to weigh the cost-benefit ratio of EER activities both in terms of energy savings and IAQ at the same time, and this could be an area of exploration for future research.

Estimation of AAER using a blower door test has its pros and cons. Blower door test is a more robust technique of building envelope air-tightness measurement with a reasonable degree of measurement confidence compared to the tracer gas decay technique [95] which is also used to measure air exchange rates. Measurement of ACH50 using a blower door test is less sensitive to parameters like weather and wind conditions. In addition, it is unaffected by the limitation of poor mixing of the tracer gas in the indoor air. Note that in homes with continuous mechanical ventilation systems installed, the ACH50 measurement taken with the blower door test often performs as if there is no mechanical ventilation present in the building due to unforeseen circumstances like the mechanical ventilation exhaust vent damper being shut due to blower door induced depressurization of the building. We only had a few of these types of homes in our data set. Hence, we decided to use the AAER as a measure of home air-tightness as it considers some of the building characteristics and weather of the building location. However, more research is needed to better represent building airtightness when the MV systems are intermittent in operation, as was seen in some homes that were not included in the data analysis for this paper. Also, there are potential sources of AAER estimation errors in homes with dedicated outdoor air supply duct integrated with the air handler which can be mitigated in future research if the air handler ductwork is investigated in further detail.

EER scoring scheme developed in this paper also has its limitations. We only accounted for the air-sealing activities that were visible from the living space and the exterior of the building. EER contractors also focus on air-sealing the attic and crawlspaces to minimize air leakage through the penetrations of the attic and floor by electrical conduit chasing and plumbing. The inherent limitation of the EER scoring scheme is the capacity to evaluate the effectiveness of various air-sealing activities done to the building envelope without considering the attic and crawlspace. The inclusion of air-sealing features these additional spaces can potentially improve the Model 2 for predicting AAER. Identification of exact leakage sites in the building shell is possible with techniques like pressurization test with smoke puffer.

3.4.6 AAER and IAQ indicators

The differences in air exchange rates across different categories was investigated by their cross-tabulation in a contingency table with AAER (Table 3. 5).

Table 3. 5 Cross-tabulation of various IAQ indicators with AAER (N=216). Statistically significant or marginally significant p-values (at α=0.05 and 0.1, respectively) are shown in bold.

	AAER [hr^{-1}]			
Categories	n	Median	Range	p-value*
Window condensation				
Absent	192	0.55	0.16-2.2	0.32
Present	22	0.54	0.10-1.7	
Mold on walls/ceiling				
Absent	145	0.52	0.10-2.0	**0.018**
Present	69	0.58	0.17-2.2	
Stains on walls/ceiling				
Absent	90	0.49	0.17-1.7	**0.0011**
Present	124	0.61	0.10-2.2	
Dampness on walls/floor				
Absent	168	0.53	0.16-2.0	0.29
Present	46	0.59	0.10-2.2	
Leaky pipes				
Absent	195	0.53	0.10-2.2	0.10
Present	19	0.62	0.17-1.7	
Used candles present				
Absent	113	0.57	0.16-1.9	0.41
Present	100	0.52	0.10-2.2	
Indoor dust level				
Low (MIDS [a] < 2.5)	184	0.51	0.10-2.2	**0.0064**
High (MIDS > 2.5)	30	0.76	0.25-1.7	
PIAQ survey results				
Freshness of indoor air:				
Fresh	131	0.52	0.16-1.9	0.21
Not fresh	83	0.58	0.10-2.2	
Odor level:				
Very/Somewhat acceptable	183	0.52	0.10-1.9	**0.052**
Not acceptable	31	0.62	0.17-2.2	
Room-to-room variation in temperature:				
None/Somewhat	176	0.56	0.10-2.2	0.821
A lot	38	0.51	0.22-1.4	

* One-way ANOVA p-values

[a] MIDS=Median Indoor Dust Score

Homes with higher number of mold sightings during the walkthrough surveys also had a 11.6% higher median AAER. This was counter-intuitive in the conventional notion that very tight homes can trap humidity indoors (generated from indoor sources like showering and cooking) for longer periods of time. This can create favorable conditions of mold growth if the humid air leads to condensation after coming in contact with cooler surfaces. One possible explanation for leakier homes with observations of mold growth could be that the leakier homes had a greater probability of outdoor mold spores infiltrating in the indoor environment. The infiltrated mold spores could then find damp locations with stagnant air, which were suitable for sustained mold growth and proliferation. Past studies have found that most indoor fungi found in homes come from outdoor air [96]. Another major cause of mold in low income homes is leaky pipe or unsuspected leaks behind walls[97] which would be another source for outdoor mold growth. Homes with observed mold growth were also found be older with the median age of 66 years, compared to the median age of 58.5 years for homes with no mold growth observed.

Based on dust level indoors indicated by the 5-point MIDS, the homes with MIDS greater than 2.5 were also found to be 48% leakier than other homes, which could have led to more outdoor dust infiltration. To investigate this possibility further, the homes with “high” versus “low” MIDS were compared with each other in terms of the mean distance of the home from the closest major road. It was found that the mean (± standard deviation) distance of high MIDS homes from the closest major road was 189±136 m, which was significantly less than the low MIDS homes, which was 294±258 m (K-W test: $p=0.047$). These results indicate that the leakier homes nearer to major roads have the potential to have higher outdoor dust levels infiltrating indoors. Much of this dust is traffic related and could contain toxic components such as tire and brake-wear, road paint [98] as well as combustion-related particles such as black carbon [99].

PIAQ responses showed marginal significance in terms of AAER difference between the groups ordered according to acceptable odor level. It was seen that the homes in which indoor odor was reported by the surveyor as being “not acceptable” were 19.2% leakier than the homes with the odor perception being reported as “acceptable” or “somewhat acceptable”. This result is interesting and suggests that the odors could be related to outdoor air pollution. The median distance of the homes with unacceptable odor level from the closest major road was 173m which was 24% lower than the median distance of other homes which was 227m, however this result was not statistically significant (Wilcoxon’s test: p=0.53).

3.5 Conclusions

The CHEER study showed that EER homes are not necessarily very airtight, and IAQ can be poor even in very leaky homes.

While EER activities do have a significant impact on increasing air-tightness, there remains much variation in building air exchange rates due to both the quality of and the specific type of EERs preformed. Inherent building characteristics like age and volume were found to affect AAER more significantly than air-sealing EERs. When it comes to the air-sealing EERs, the homes with air handler ductwork sealing and window weather-stripping were found to be significantly tighter than those which did not have these EERs. Based on the significant decrease in AAER by increasing EER-scores, it can also be said that the homes with one or more of air-sealing EERs present in the house can also expected to be significantly tighter. Indicated IAQ was also significantly affected by more than one building characteristic including airtightness. This study showed that homes with higher ventilation do not necessarily have better IAQ, and homes with higher AAER can also have poorer IAQ as indicated by household walkthrough observations of visible mold growth, stains, indoor dust and perceived odor. Indoor dust level was found to be the highest in the leakiest homes located close to major roads. Hence, EER interventions also have a potential to lower traffic related pollutant exposure in low-income households if more quality control is practiced during EER implementations. This study shows that there are opportunities of further improving building air-tightness in low-income housing which can not only increase home energy efficiencies further, but also improve IAQ in the long run.

3.6 Acknowledgements

The authors would like to thank Xcel Energy for their genuine support, all the participating households, and Environment Protection Agency for funding the project (EPA-G2014-STAR-A1, Miller). We thank all the household participants of the CHEER study, the partner agencies, our advisory board and all the research assistants who helped implement this study: Adam Pittman, Adam Hahn, Adam Hester, Sarah Hong, Caio Pires, Stefano Brunelli, Alex Mass, Alisen Bol, Jonathan Kohlenberg, Olivia Cecil, Tess Bloom, Sam Rock, Ethan Zerpa Blanco, Ryan Hourigan, Hanadi Salamah and Mohamed Eltarkawe.

3.7 Supplements

Table S3. 1 Walkthrough 1 survey observations and options

Observations	**Options**
How tall is the building?	Number of stories
Wind shielding category of the building location [a]	Categories: 1,2,3,4,5
Elevation above sea level	# [ft]
Radon mitigation system installed	Yes/No
Weather-stripping in door frames	All, most, some, none
Weather-stripping in windows	All, most, some, none
Attic insulation	Yes/No
Foam sealing visible in cracks	Yes/No
Furnace ductwork sealing	Yes/No
Continuous mechanical ventilation present	Yes/No
Furnace type	Gas/Electric
Furnace air filter	Standard pleated/Electrically enhanced/other/filter inaccessible

[a] Wind shielding by the immediate surroundings:

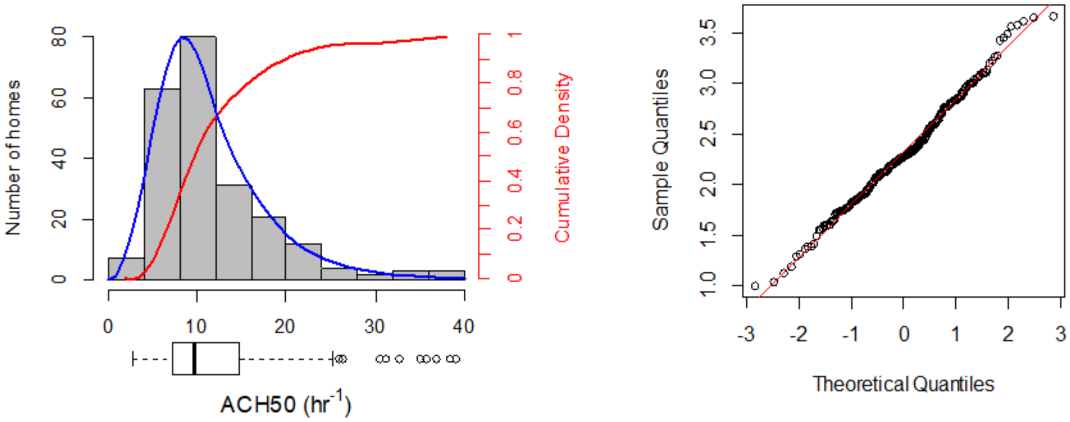


Figure S3. 1 Distribution of ACH50 in all the test homes: Left: Histogram showing log-normal distribution; Right: Q-Q plot showing agreement of ln(ACH50) quantiles with theoretical normal distribution quantiles.

Table S3. 2 Walkthrough 2 observation table with corresponding options for various household characteristics

Observations	Options
Room dimensions	Length, width and height [ft]
Floor type	Concrete, tile, wood, PVC [a], Pergo, Linoleum, Carpet, Stone, Adobe, Other
Door to outside	Yes/No
Operable windows	Number in each room
Fixed windows	Number in each room
Window condensation present	Yes/No
Room exhaust fan present	Number in each room
Window air conditioner	Number in each room
Cooking stove	Gas, Electric, other, NA [b]
Stove hood	Exhausts outdoors, Exhausts indoors, absent, NA
Fireplace	Wood, gas, other, No fireplace
Woodstove	Gas, wood, not present
Humidifier	Yes/No
Cleanliness	Good, fair, poor
Odor	1(least) to 5(extreme) number scale
Dampness (perceived by touch)	Yes/No
Visible Stains	Yes/No
Leaky Pipes	Yes/No
Visible Mold	Yes/No
Stuffed toys present	Yes/No
Visible dust present	1 (min.) to 5(max.) number scale (increments of 1)
Food remains present	Yes/No
Mouse traps	Number present in the room
Dead bugs	Yes/No
Spider webs present	Yes/No
Used candles present	Number present in the room
Noticeable drafts present	Yes/No

[a] Poly vinyl chloride

[b] Not applicable

Table S3. 3 Summary of the occupant demographics in the CHEER study.

Participant demographics	Total N=475 (100%) Number of people [b] N (% of total)
Region:	
Aurora	95 (20.00)
Boulder/Ft. Collins	77 (16.21)
West Denver	153 (32.21)
Central/North Denver	131 (27.58)
Other	19 (4.00)
Sex:	
Female participants	294 (61.89)
Male participants	176 (37.05)
Not answered	5 (1.05)
Age groups (years of age):	
8 to 13	40 (8.41)
14 to 18	24 (5.05)
19 to 35	63 (13.26)
35 to 50	98 (20.63)
51 to 65	109 (22.95)
>65	108 (22.74)
Race/Ethnicity	
Hispanic	107 (22.52)
Non-Hispanic White	123 (25.89)
Non-Hispanic Asian	11 (2.31)
Non-Hispanic Black	11 (2.31)
Non-Hispanic Other	11 (2.31)
Unidentified	182 (38.31)
Education	
Less than high school	109 (22.95)
High school	159 (33.47)
Some college	55 (11.57)
Bachelor’s degree or higher	126 (26.52)
Missing/Refused	26 (5.47)
Employment status	
Employed (Full/Part time)	190 (40.00)
Not employed	123 (25.89)
Missing/Refused	162 (34.10)

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[b] All the occupants in the CHEER study households

Chapter 4

Impacts of Outdoor Air Pollution on Indoor Air Quality in Low-Income Homes During Wildfire Seasons

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4.1 Abstract

Indoor air quality is often degraded because of the infiltration of outdoor air pollution. In addition, air-sealing activities geared towards improving home energy efficiency reduce air-exchange rates. As part of the Colorado Home Energy Efficiency and Respiratory Health (CHEER) study, we evaluated the infiltration of outdoor air pollution in low-income homes during the 2016 and 2017 wildfire seasons (June through October), when outdoor air pollutants are often at their highest in Colorado with wildfire smoke plumes being superimposed with traffic emissions and other local urban air pollution sources. Simultaneous indoor and outdoor measurements were taken of $PM_{2.5}$, BC, O_3, CO, and NO_2 for two to seven days in each home to capture the concentrations of significant pollutants markers for traffic and wildfire related emissions. Results indicate that during periods of wildfire plumes indoor $PM_{2.5}$ concentrations were up to 3.6 times higher compared to periods with no wildfire plumes. The median I/O ratio of CO was found to be the highest among all the pollutants in all cases. While the outdoor and indoor concentrations of BC was primarily affected by road proximity, NO_2 was found to be primarily affected by the presence of gas stoves more than road proximity. Mechanical ventilation systems were also found to increase the I/O ratio of $PM_{2.5,}$ BC and O_3 by 18%, 4%, and 5% respectively. Window opening had the most significant impact on elevating BC concentration indoors. The results of this study are helpful in identifying the major causes of indoor air contamination during wildfire seasons and to strategize activities that mitigate the negative impacts of outdoor air pollution.

4.2 Introduction

Indoor environments of homes are meant to keep us safe against the undesirable natural elements including outdoor air pollution. However, air exchange with the surroundings is an integral part of a home for ventilation and ensuring the health and well-being of the occupants. Although the primary objective of home ventilation is to supply fresh air to the home interior, infiltration and natural and forced ventilation pathways can also introduce outdoor air pollutants indoors.

In addition to indoor sources of air pollution, infiltration of outdoor air pollutants also degrades the air quality in homes. This is especially important in buildings located in cities that experience elevated outdoor air pollutant concentrations. Since we spend the majority of our time in any day indoors (often at home)[100], a better understanding of the building characteristics that govern the infiltration of outdoor pollutants is essential to determine our exposure to those pollutants. Studies have shown that infiltration rates of fine particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) are higher in homes compared to coarse and ultrafine particulate matter [101–103] and that wildfire smoke takes a few minutes to an hour to infiltrate indoors, but persist for eight to ten hours after reaching a maximum value[104]. Many past studies have concluded that staying indoors combined with the use of air-cleaners can effectively reduce $PM_{2.5}$ exposure during wildfire seasons [105–108]. The use of air-cleaning technology is often overlooked, however, in many communities due to cost and lack of information.

The highest levels of outdoor air pollution in the Denver metro area of Colorado can be expected during the summer wildfire season (the months of June through October of every year). During this time of the year, outdoor particulate matter levels are elevated due to the usual background level of traffic related air pollution superimposed with suspended aerosols produced by both short and long-range wildfires which are increasing in number over the decades as a result of climate change [109,110]. Moreover, people living in homes situated near a major road or a highway are exposed to significantly higher levels of other traffic related air pollutants like black carbon (BC), carbon monoxide (CO), and nitrogen dioxide (NO_2), all of which have been associated with adverse health effects including increased risk of cardiovascular diseases, COPD, stroke and reduced life expectancy [111–113]. NO_2 is also a known respiratory tract irritant and marker for traffic-related air pollution [114]. Ozone (O_3) is also elevated during the summer months and is currently a major air quality health problem in the Denver metro area [115]. Denver is currently out of compliance with the National Ambient Air Quality Standards (NAAQS) and has been classified by the EPA as a moderate nonattainment area which has led to the state of Colorado's submittal of a State Implementation Plan (SIP) in May 2017 [116].

Past studies have documented that outdoor air pollution degrades the air quality in offices, schools, hospitals, and commercial buildings through the mechanical heating, ventilating and air-conditioning systems and infiltration [117–121]. There are limited data, however, related to the infiltration characteristics of outdoor air pollution in low-income homes. While everyone living in the same geographical location are affected at the same time by outdoor air pollution, low-income populations are considered more vulnerable to the effects of climate change and outdoor air pollution due to lower financial capacity to adapt to rapidly changing environmental conditions and disease transmission [2,122,123], thus an important community to consider.

Many low-income homes throughout the United States have received energy retrofit assistance through the Weatherization Assistance Program (WAP) introduced through the U.S. Department of Energy (DoE) since 1976. One of the strategies that WAP focuses on for energy efficiency improvement of residential buildings is air-sealing of building envelopes to minimize the leakage of indoor conditioned air and hence reduce energy costs. This, in turn, can also affect the infiltration rates of outdoor pollutants.

In this study, we evaluated the infiltration characteristics of some key air pollutants that are markers for traffic- and wildfires-associated pollutants in low-income residential buildings, many of which received energy-efficiency retrofits. The key objectives of this study were to better understand how the indoor air quality of low-incomes homes is impacted by outdoor air pollution during periods of high concentrations because of wildfires, and what features of the buildings are important for reducing indoor exposures to outdoor air pollution. The study consisted of monitoring homes during periods of elevated outdoor air pollution for a suite of air pollutants as well as collecting detailed building characteristics and time-activity diary information.

4.3 Methods

4.3.1 Study Recruitment

Households located in Denver and the northern front range of Colorado were recruited for this part of the CHEER study through letters mailed to homes that met the low-income criteria set by Low-Income Energy Assistance Program (LEAP) in the state of Colorado. This mailing was accomplished through a partnership with Xcel Energy Inc. and Boulder Housing Partners[124]. A subset of these homes had also received energy efficiency retrofits from the federal WAP. Homes were recruited for the study only if all the home occupants were nonsmoking to eliminate smoking as a source of bias in the collected dataset.

Once a home was recruited, a home visit was conducted which lasted approximately two hours. During each home visit, data were collected using a blower door test, air quality monitoring instrumentation both indoors and outdoors, and a walk-through survey of the home noting key home characteristics. Each household was given a $25 gift card to incentivize participation, once during instrument setup and once during instrument pickup. Prior to beginning the recruitment process, compliance approval was obtained from the University of Colorado Boulder's institutional review board (Protocol 14-0734) for performing this scientific study involving human subjects.

4.3.2 Building Air Tightness

Each home was tested for air tightness using a computer automated multi-point depressurization blower door test (Minneapolis Model 3 Blower Door with DG-700 digital pressure gauge, Minneapolis MN). Details of this test are reported in another paper describing a larger sample from the CHEER study (Chapter 5). Air tightness of each building was reported as air changes per hour at a pressure of -50 Pa with respect to outdoors (ACH50). The annual average air exchange rate (AAER) values were also estimated using the LBNL infiltration model[78] that is built into the software used for the automated blower door testing. [79] The LBNL model considers the climate zone of the location, number of bedrooms, building dimensions, indoor and outdoor temperatures, and wind shielding category. The AAER values were also adjusted if the homes had continuously running mechanical ventilation (MV) systems.

4.3.3 Time Activity Diary

The home occupants were also asked to fill out a diary of activities in which they recorded the number of hours of spent performing specific activities during the sampling period. The activities included cooking, leaving exterior doors or windows open, running air conditioning units or swamp coolers, running kitchen or bathroom exhaust fans and noting the times when none of the occupants were home (pets could still be home).

4.3.4 Instrumentation

Simultaneous continuous measurements of air pollutants were taken both indoors and outdoors for two to seven days in each home. Pollutants of interest were identified based on the regulatory standards and public health implications, availability of reference scientific data to validate our measurements, availability of low-cost instruments, and budget constraints. The use of low-cost instruments was prioritized to collect data from at least five homes at a time when either a short or long-range wildfire plume impact could be identified in the study region. Table 4. 1 lists all the pollutants measured along with corresponding instruments or techniques used. BC and NO_2 were initially not sampled for the 2016 deployment period but were added on during our 2017 sampling campaign to capture more specific traffic-related air pollutants (TRAP).

Table 4. 1 List of parameters and pollutants measured during the study.

Parameter	Unit	Instrument/Method	Accuracy Notes
Building air tightness	Air changes per hour at an indoor-outdoor pressure difference of 50 Pa (ACH50 [hr^{-1}]) and annual average air exchange rate (AAER [hr^{-1}])	Blower door test (Minneapolis Blower Door Model 3 with DG-700 pressure gauge)	Flow accuracy ±3% [125]
$PM_{2.5}$	Particles per cubic feet [#/cm^3]	Dylos 1700 Air quality monitor	R^2 = 0.7 compared to TEOM-FDMS[b] [126]
Black Carbon (BC)[a]	Nanograms per cubic meter [ng/m^3]	microAeth AE51Aethalometer	Precision: ±0.1 µg BC/m^3 @ 1 min avg [127]
Ozone (O_3)	Parts per billion [ppb]	Y-Pod (metal oxide sensor)	Max. RMSE [c] = 7.9 ppb
Carbon monoxide (CO)	Parts per million [ppm]	Y-Pod (electrochemical sensor)	Max. RMSE = 0.16 ppm
Nitrogen dioxide (NO_2)	Parts per billion [ppb]	Ogawa passive sampler with pre-coated NO_2 sampling pad	± 5% of measurement [128]

[a] Total black carbon (not size resolved)
[b] Tapered element oscillating microbalance (TEOM) and Filter Dynamics Measurement System (FDMS) [129]
[c] Root mean squared error from calibration curve generated with co-location experiments with federal equivalent monitor

To establish significant confidence in our measurements from the low-cost instruments, co-location experiments were performed with federal equivalent monitors (FEM) from the Colorado Department of Public Health and Environment (CDPHE) for instrument calibrations as well as data validation.

4.3.4.1 Particulate matter

Number concentrations of PM were measured using the low-cost Dylos-1700 air quality monitors (Model 1700, Dylos Corporation, Riverside, CA). Dylos-1700 is a laser-based optical particle counter that reports the number concentrations (particles per cubic feet) of PM in two size bins: small particles with diameters 0.5 microns and above, 0.5 microns being the lower detection limit of the instrument, and large particles with diameters 2.5 microns and above. The difference between these two reported values represents the number concentration between 0.5 and 2.5 microns in particles per cubic feet ($PN_{0.5\text{-}2.5}$, referred to as $PM_{2.5}$ from here on for simplicity).

4.3.4.2 Black Carbon

Real time black carbon (BC) data were collected using microAeth® AE51 aethalometers (AE51; AethLabs, San Francisco, CA, USA), which are based on optical measurement of light transmission through a 3-mm spot created on a white filter strip containing insert of T60 Teflon-coated borosilicate glass fiber filter material. Each aethalometer was loaded with a fresh filter strip before sampling and was connected to a power supply via a DC power adapter during sampling. Sampling frequency was set to 60 seconds to match the sampling frequency of other instruments being used and a flow rate setting of 50 ml/min was chosen with the expected high filter loading rates for near-road outdoor sampling since most of the study homes were near to high density trafficked roads. Preliminary evaluation of time series data after sampling showed that the data had significant noise and low signal-to-noise ratio. The Optimized Noise-reduction Algorithm (ONA) developed by the US EPA [130] was used for smoothing of the time series data which also resulted in the removal of any negative data values.

4.3.4.3 Gas phase pollutants

Custom-built open-source low-cost instruments were used for the measurement of O_3 and CO (Y-Pods, Hannigan Lab, University of Colorado Boulder[131]). Y-Pods are based on an Arduino platform [78] with on-device data-logging capacity on a micro-SD memory card. They use a combination of electrochemical and metal oxide sensors. The Y-Pods stored data in the form of a raw voltage signal from the sensors. Co-locations with reference instruments were crucial for the conversion of the raw voltage signals to meaningful pollutant concentrations. A post-processing algorithm was used for assimilating the co-location generated calibration curves with the field data. [132] Co-location experiments were performed in both 2016 and 2017 at the Colorado Department of Public Health and Environment (CDPHE)'s Continuous Air Monitoring Program (CAMP) station in downtown Denver[133] for calibrating the CO and O_3 sensors of Y-Pods.

Passive samplers from Ogawa Inc. (Ogawa, Pompano Beach, Florida, USA) were used for both indoor and outdoor measurement of time-weighted average (TWA) concentrations of NO_2. The passive sampler consists of a pre-coated sample collection paper pad coated with Triethanolamine placed inside a Teflon sampler body and secured in place by diffusion end caps. The samplers retrieved from the field were shipped to Ogawa Inc. for lab analysis along with field blanks for blank correction. Proper sampler storage, sampler preparation, and sampling protocols were followed according to the specifications from the manufacturer. All the samples were blank-corrected.

4.3.4.4 Instrument rigs

All the instruments were mounted on camera tripods using custom attachments and appropriate weather protection of the outdoor instrument rigs. The Y-Pods were, by design, weather resistant. The Dylos-1700 and microAeth AE51 aetholameters were weather-protected with appropriately sized inverted metallic buckets bought from local hardware stores. The Dylos monitors (and protective buckets for the outdoor monitors) were securely mounted at a height of 50 inches from the ground level on a wooden arm attached to the main axis of the instrumentation rig camera tripod with the intake and exhaust vents of the monitors facing down towards the ground. This orientation ensured safety against accidental introduction of water droplets or foreign objects into the instrument intake vent, and also prevented direct beams of light to enter the instrument which could potentially cause measurement errors. To avoid any chances of the buckets accumulating static charge due to wind friction that might have led to biased measurements of aerosol concentrations, the buckets were grounded using conductive wires. To ensure fairly unbiased sampling of air from the breathing zone in any home, instrument rigs (tripods) were set up indoors so that they were at least two feet away from any wall, fully extended tripod height of 1.5 m, were in a different room than with a combustion appliance, at least five feet away from any fireplace or woodstove, not immediately adjacent to an exterior window (home occupants were asked not to open the window during sampling period if the rigs had to be set up next to an operable window because of space and convenience constraints). Outdoor rigs were set up between 0.6 – 3 m away from the home itself in the backyard of the home depending on space availability.

4.3.4.5 Data filtration

One-minute resolution time series data of $PM_{2.5}$, BC, CO, and O_3 concentrations in each home indicated that indoor pollutant concentrations could spike for short periods by orders of magnitude above the outdoor level during indoor source-induced events like cooking (the indoor source events were verified with the time activity diaries filled out by the participants). Several past studies have also found similar scenarios and have found that indoor $PM_{2.5}$ concentrations are generally higher than outdoor levels [134–136].

Since we were interested in the infiltration indoors of outdoor pollutants, data were analyzed using only the time intervals during which there were no indoor source-related events directly affecting the indoor pollutant concentrations. Time series data were filtered by visual inspection and the data were removed that corresponded to the times when huge spikes in the indoor concentrations appeared with a rapid increase, reaching a maximum value in less than an hour, followed by an exponential decay. Data filtration was done from the beginning of each spike until the tail of the indoor spike was roughly horizontal after the decay (**Error! Reference source not found.**). The remainder of the data were then analyzed as a filtered set of data (and will be referred to as "filtered data" from here on). Past studies have also taken a similar approach to filter out the effect of indoor source-related spikes in pollutant concentrations[135].

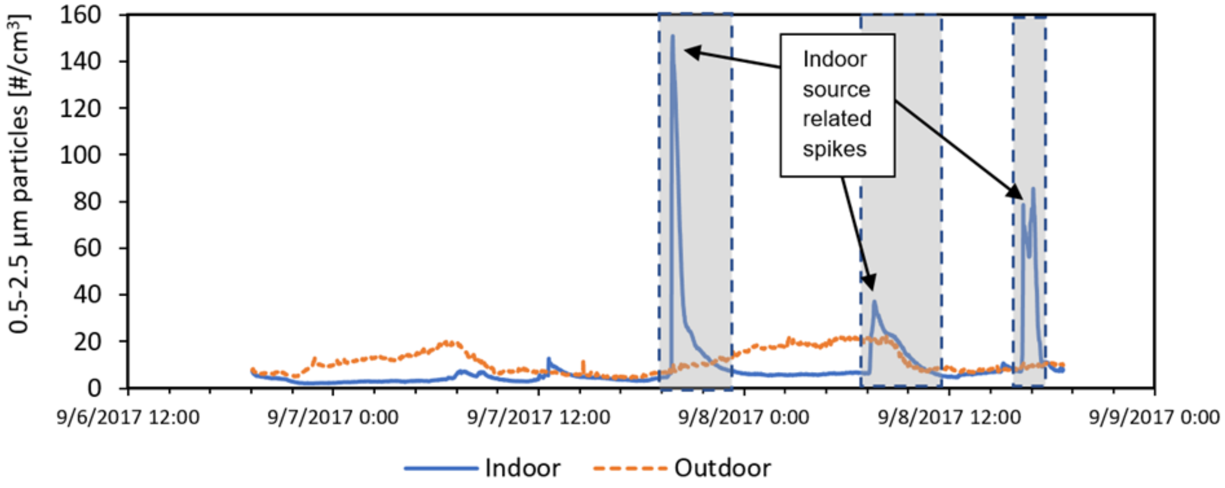


Figure 4. 1 Example from one of the study homes showing the data filtration process. Time series data from the shaded regions were removed, and the remainder of the time series was treated as "filtered data". The original dataset without filtering is referred to as "raw data".

For NO_2 data, the homes with gas stoves were not included in the assessment of the impact of outdoor pollutants because both past studies [137–139] and our data showed that homes with gas stoves had significantly high indoor NO_2 concentrations, whereas a goal of this study was to investigate only the infiltrated component of the outdoor NO_2 in homes.

4.3.5 Wildfire impacts

Remote sensing data on wildfire smoke plume PM mass density from the National Oceanic and Atmospheric Administration's Hazard Mapping System[140] (NOAA HMS) were used for categorizing the mesoscale impact level of wildfire smoke plumes on the study region. The plume PM density from NOAA HMS is based on area coverage of wildfire-related smoke plume aerosols optically detected by MODIS and GOES satellites, and the satellite imagery is visually analyzed by experts each day. The plume is categorized into three levels of smoke-related PM densities[141]: the "low" category corresponds to the smoke PM density ≤ 6 μg/m^3, the "medium" category corresponds to smoke PM density of ≤ 15 μg/m^3 and "high" category corresponds to smoke PM density ≤ 27 μg/m^3.

4.3.6 Distance from the closest major road

The distance of the enrolled homes from the closest major roads were evaluated based on the Online Transportation Information System (OTIS) database maintained by the Colorado Department of Transportation (CDOT) [142] where a major road was defined as a road with annual average daily traffic (AADT) of greater than 10,000 [84,143,144]. Homes were grouped according to the distance of < 100 meters, 100 to 200 meters, and >200 meters of a major road based on the evidence from past studies that traffic-related air pollutant concentrations drop down to background levels after moving away from the major road between 100 and 200 meters [145,146].

4.3.7 Statistical Data Analyses

Data were analyzed using the R programming language (Version 3.4.4). Categorical dummy variables were used when grouping the data into different categories. For continuous variables, first the sample distributions were investigated using histogram plots. If the data showed distinct visual features like that of a normal or lognormal distribution, an Anderson-Darling (A-D) test was used in addition to quantile-quantile (Q-Q) plots to confirm the normal (or lognormal) distribution of the data. If the A-D test failed to reject the null hypothesis of the normality assumption ($p>0.05$) in the sample distribution, a two-sample t-test with unequal variances was used to test for statistical difference in means between two groups and one-way analysis of variance (ANOVA) for more than two groups (tests performed on log-transformed data). As per the need, Tukey's honestly significant difference (Tukey HSD) post-hoc test was conducted after ANOVA to investigate pair-wise significance in the difference of means between groups. If a significant deviation ($p<0.05$) from the normality assumption was reported by the A-D test, the non-parametric Kruskal-Wallis (K-W) test and Wilcoxon Mann-Whitney (U) tests were used for statistical comparison of sample medians. Linear regression analysis was also performed to investigate the strength and statistical significance of association between two continuous variables of interest. Correlation between variables (r) are reported as Pearson's correlation coefficient unless otherwise stated. Level of significance of 5% ($p=0.05$) was used in all the statistical tests and a p-value of 0.05 to 0.1 was defined as marginal significance.

4.4 Results and Discussion

4.4.1 Study homes

A total of 28 homes were tested for the study, 10 homes during 2016 and 19 homes during 2017 wildfire seasons in the Boulder, Longmont and Denver regions of Colorado. Because of the differences observed in household demographics, the recruited home locations were segregated into four major regions: Aurora (East Denver), Boulder/Longmont, West Denver and Central/North Denver (Figure 4. 2). Thirteen of the homes were energy-efficiency retrofitted (EER) under the WAP program and 10 of the homes were conventional non-energy-efficiency retrofitted homes (Non-EER). Five homes were specially built as built-green (BG) homes for improved energy efficiency by Boulder Housing Partners with airtight construction, rooftop solar panels, all-electric air heating, and water heating systems. Three of the BG homes also had heat recovery ventilation (HRV), which were intermittently and automatically operated for brief periods of time each day with timer switches. One of the homes was tested both in 2016 and 2017 field campaigns so the sampling was done 29 times in total.

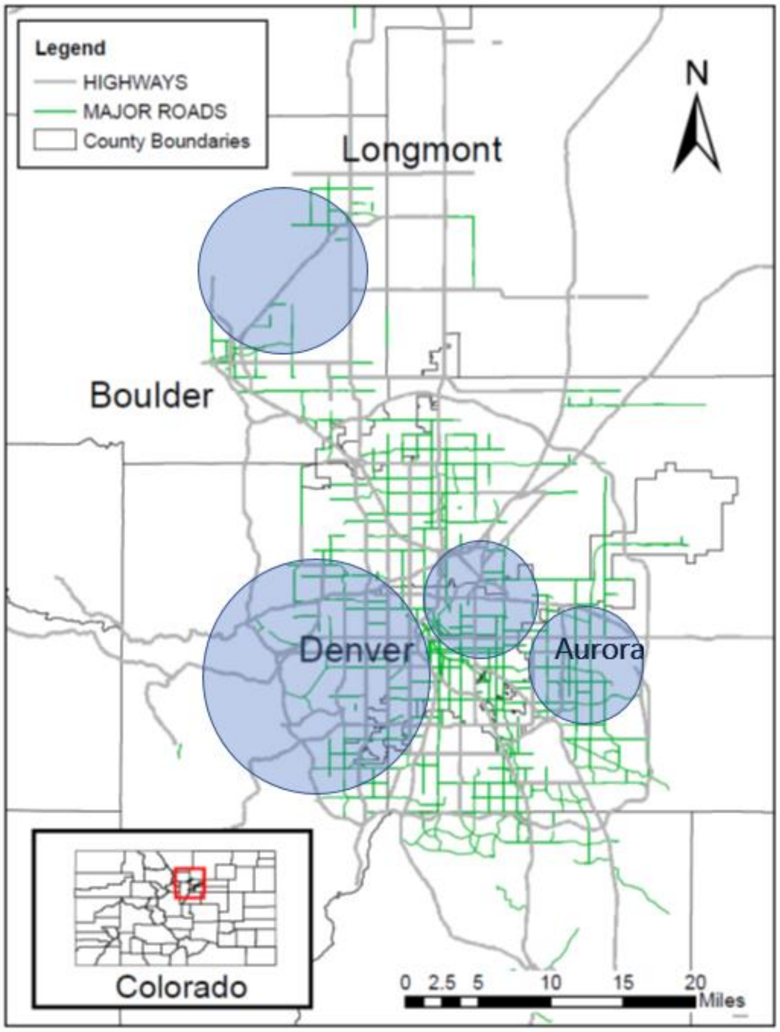


Figure 4. 2 Map of the study region (shaded circles indicate areas of recruited homes and size of circles indicate the number of homes studied in each region).

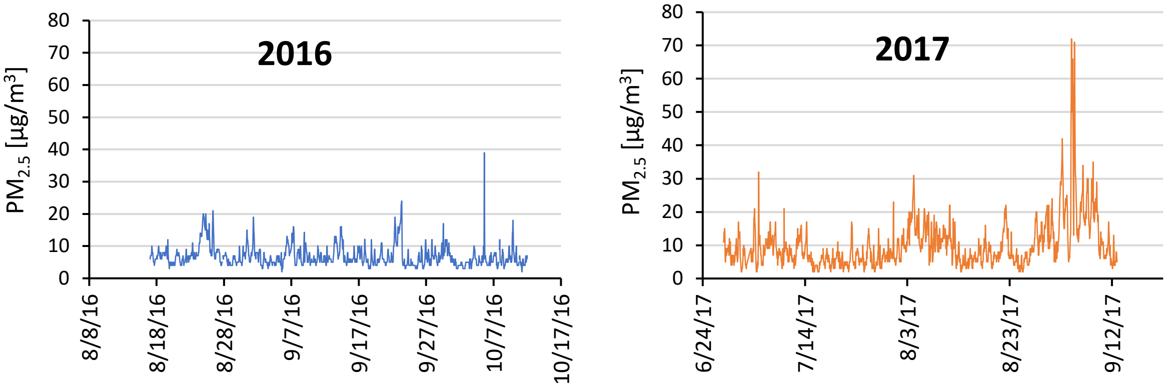
4.4.2 Building Airtightness

Log-transformed ACH50 as well as AAER were found to be lognormally distributed (A-D test: $p>0.05$). As expected a significant linear relation was found between AAER and ACH50 (F (1,26) =315.81, $p<0.000$). This was expected since ACH50 is an input to the model that estimates AAER. Since AAER also includes housing and location characteristics and weather impacts, this parameter is a reasonable representation for home ventilation on an annual average basis.

The impacts of building characteristics on AAER were investigated which showed that the air-tightness in the study homes ranged from the lowest AAER value of 0.22 hr^{-1} (ACH50=4.1 hr^{-1}) to the highest AAER of 1.3 hr^{-1} (ACH50=22 hr^{-1}). The results of one-way ANOVA on ln(AAER) and ln(ACH50) for the various groups also shows that none of the groups had statistically significant difference according to building air-tightness ($p>>0.05$).

4.4.3 Wildfire impacts on the study region

Elevated $PM_{2.5}$ mass concentrations were recorded (Figure 4. 3) at the ground surface level in Colorado Department of Public Health and Environment (CDPHE)'s Continuous Air Monitoring Program (CAMP) station in downtown Denver, Colorado. Instrument inlets are located on the roof of the CAMP station, which is located at a busy intersection and so often experiences high levels of traffic-related air pollution.



(a) (b)

Figure 4. 3 Hourly surface concentrations of PM2.5 measured at CAMP air monitoring station in Denver in (a) 2016 and (b) 2017 deployment periods (measurement instrument was a GRIMM EDM 180 optical monitor).

CAMP site data indicated that during the 2017 wildfire season, there were short periods of significant rise in outdoor PM$_{2.5}$ levels which coincided with several days of reduced visibility due to the long-range wildfire plumes from Canada and the Western regions of the United States affecting the study region. 2016, however, had comparatively low outdoor PM$_{2.5}$ during our field deployment period. Both 2016 and 2017 deployment periods had several days of outdoor PM$_{2.5}$ levels above the secondary 1-year National Ambient Air Quality Standard (NAAQS) for PM$_{2.5}$ of 15 µg/m^3. Typically, the Denver metro area is in compliance for the PM$_{2.5}$ standard[147,148].

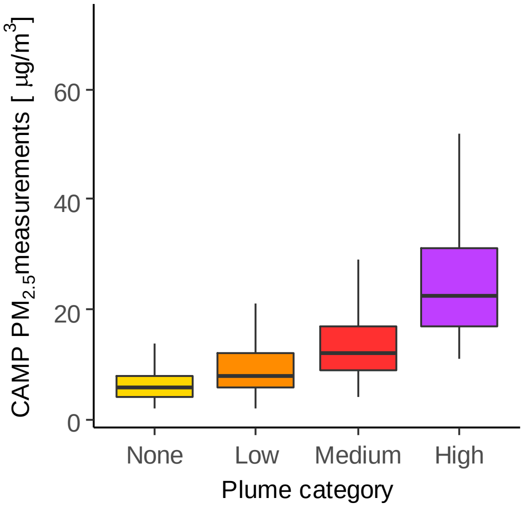


Figure 4. 4 Boxplots (without outliers) showing plume categories and the corresponding PM2.5 concentration measurements made at CDPHE (CAMP) air monitoring station in Denver. Data were pooled together from the deployment periods from 8/17/2016 to 10/10/2016 and from 6/28/2017 to 9/12/2017. (K-W test: $p<0.01$).

Study homes were categorized according to the wildfire-related plume cover density in the study region during the instrument deployment period, based on NOAA HMS satellite imagery. Categorization of plume cover over the study region corresponded well with the ground level measurements taken at CDPHE (CAMP) air monitoring station in Denver (Figure 4. 4). The CAMP hourly measurements of median $PM_{2.5}$ monotonically increased from 6 to 8 (+33%), 8 to 12 (+50%) and 12 to 23 µg/m^3 (+92%) between the plume categories "None", "Low", "Medium" and "High" respectively (K-W test: $p<0.05$). This suggests that the categorization scheme based on NOAA HMS data was a reasonable representation of the long-range wildfire plume cover over the study region at the surface level. The median difference between the "High" and "None" categories was 17µg/m^3, which was 2.8 times the background level (representative of traffic and other local emission sources) of 6 µg/m^3.

4.4.4 Pollutant concentrations in homes

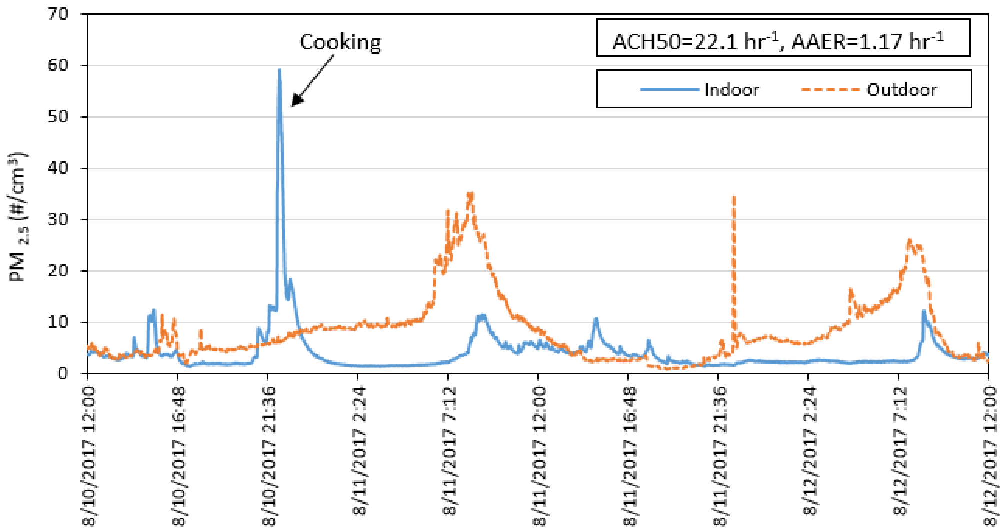
4.4.4.1 Sample sizes

The number of homes for which data were available for various measured pollutants varied due to data recovery issues. Out of the 29 sampling periods, some instruments suffered from power failure, sensor malfunction, or some other technical issue that prevented from data recording. The total number of homes for which data were available both indoors and outdoors for $PM_{2.5}$, BC, CO, O_3, and NO_2 were 26,16, 27, 21, and 16 respectively. BC and NO_2 measurements were only added in 2017 whereas the rest of the pollutants were measured for both 2016 and 2017 periods.

4.4.4.2 Particulate matter

Raw (unfiltered) time series data of indoor and outdoor $PM_{2.5}$ showed that outdoor concentrations were mostly higher than indoor concentrations except when there were spikes in the indoor concentrations caused by indoor activities like cooking. This was true even in absence of wildfire plumes. A past study conducted in 15 homes in Colorado had concluded that outdoor $PM_{2.5}$ was significantly higher for summer compared to spring and fall [149]. Cooking periods were identified based on the time activity diary, which correlated well with the indoor spikes seen in time series data. Secondary indoor source events could be observed in the data, like vacuuming or kids playing on carpet floor, that were unaccounted for in the time activity diary suggesting that participants often forgot to record their activities.

(a)



(b)

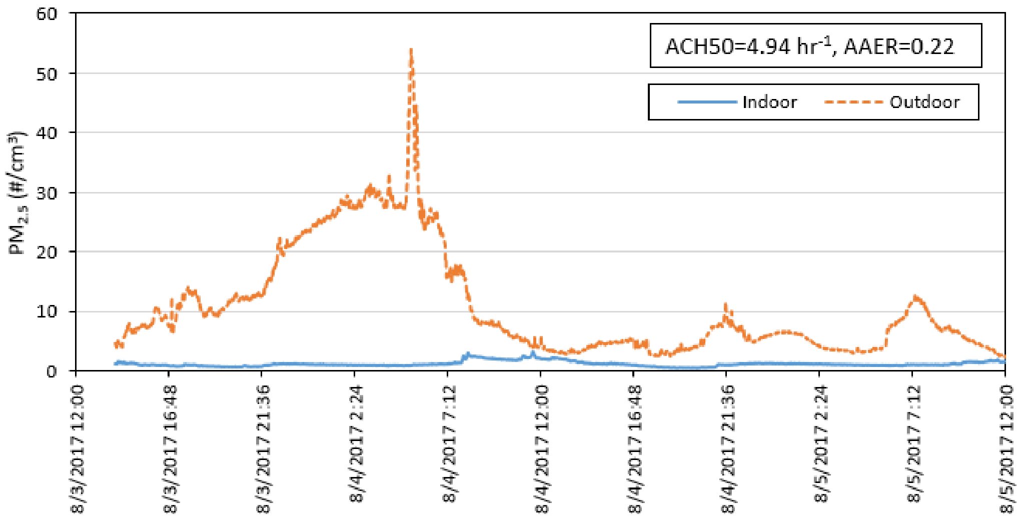


Figure 4. 5 Indoor and outdoor time series $PM_{2.5}$ data (particle number concentrations between 0.5-2.5 microns, or $PN_{0.5\text{-}2.5}$) from one of the homes tested.

Figure 4. 5 shows an example of the time series of raw PM data from two of the homes or particle number concentration between 0.5 and 2.5 microns ($PN_{0.5\text{-}2.5}$ and referred to here as $PM_{2.5}$ for simplicity). In the home shown in Figure 4. 5 (a), one cooking related spike can clearly be seen

in the indoor $PM_{2.5}$ concentration, and this home was one of the leakiest in our dataset. The field deployment period for this home coincided with a plume cover event of medium density, which explains the distinct rise in outdoor $PM_{2.5}$ concentrations compared to normal levels, lasting for roughly six to seven hours at a time. Few occasional short-term spikes in outdoor concentrations were also seen on 8/11/2017 at 22:00, which can possibly be attributed to a measurement error because its effect was not seen indoors even though at least one window in the homes was left open by the homeowners at all times. This pattern was also seen in other homes and the profiles of indoor concentrations were seen to follow the outdoor concentration spikes in most cases. Drastic differences were seen from home to home in the indoor concentration profiles which could possibly be attributed to the general cleanliness level between homes. Since most homes in our study had their windows open, we were unable to determine if the elevated indoor levels were due to the leakiness of the home. Another home shown in Figure 4. 5 (b) was a tighter home with no significant indoor source-events. All the windows in this home were closed throughout the sampling period.

The fraction of sampling times when outdoor concentrations were higher than indoors during each field deployment was also calculated using the unfiltered datasets (Figure 4. 6). It was seen from our raw dataset that outdoor concentrations of $PM_{2.5}$ were higher than indoors close to 59% of the time in most of the homes. Similarly, for the filtered dataset, the corresponding mean and standard deviation were 73% and 19%, respectively.

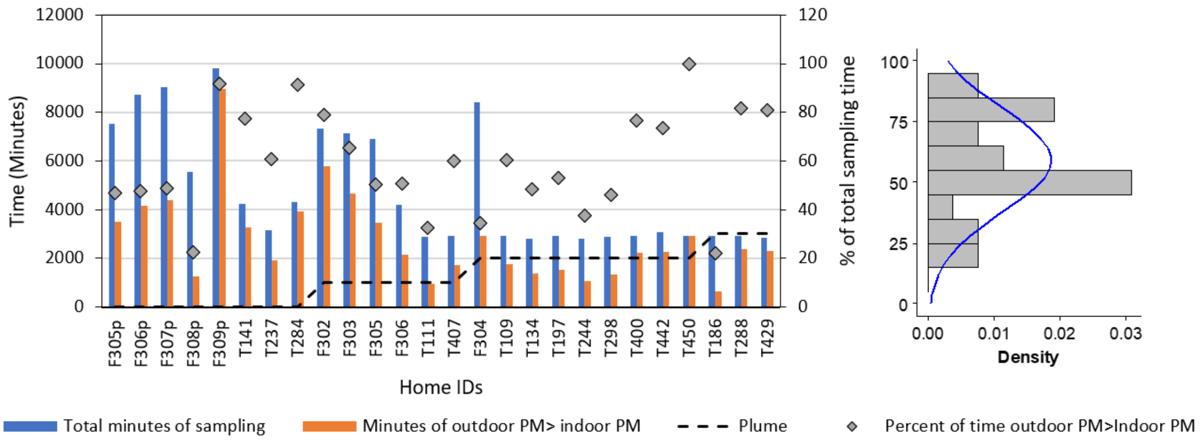
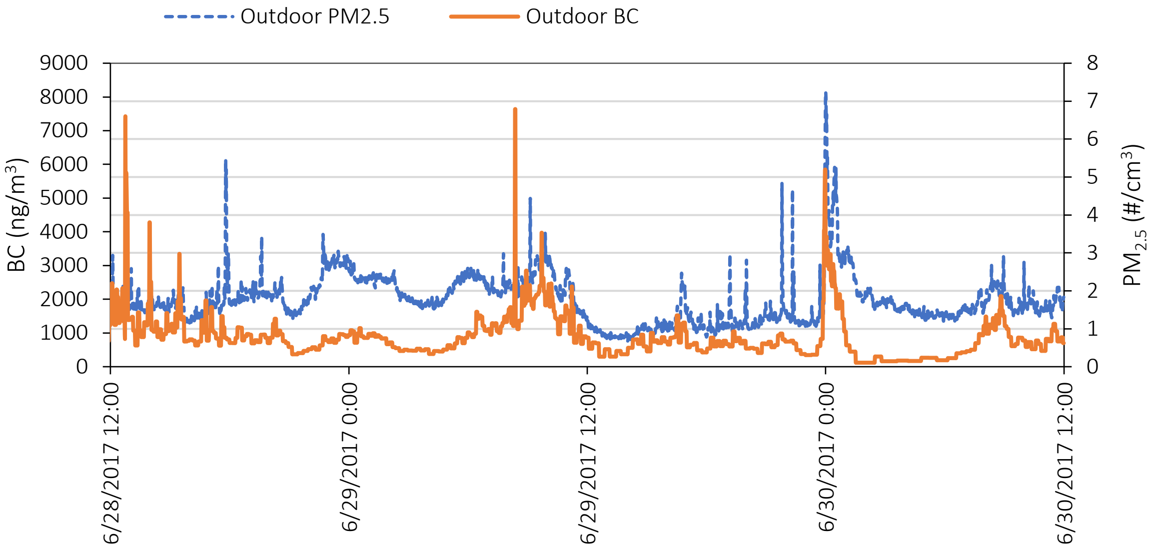


Figure 4. 6 Comparisons of total time of PM sampling (raw dataset) in each home and the corresponding probability densities shown on the right which followed a normal distribution (A-D test: p=0.49) centered at mean=59% and standard deviation =21% (n=26). Homes are arranged according to the plume categories denoted by the dashed black line. Each step of the dotted black line indicates a plume category: No plume corresponds to a value of zero, Low plume corresponds to a value of 10, Medium plume has a value of 20 and High plume has a value of 30 on the percentage axis at the right side of the plot.

4.4.4.3 Black carbon

Outdoor and indoor BC time series profiles (raw datasets) were found to be significantly correlated to each other as well as outdoor $PM_{2.5}$ (Figure 4. 7). Linear regression between geometric means of concentrations in all homes showed that indoor and outdoor BC were positively correlated (R^2=0.49, p=0.0026). Indoor BC was also correlated with outdoor $PM_{2.5}$ (R^2=0.66, p<0.000). Very few homes had indoor source-related spikes unlike $PM_{2.5}$ suggesting that most of the BC in homes originated outdoors. A past study has also shown that outdoor vehicular traffic emissions directly affect indoor PM levels despite windows remaining closed at all times [150].

(a)



(b)

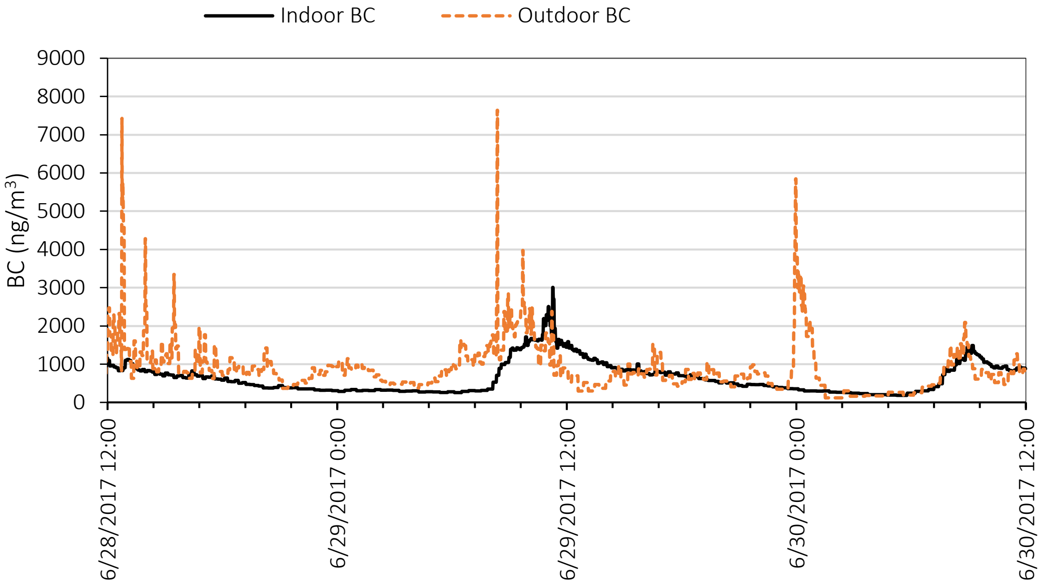


Figure 4. 7 Time series profiles of indoor and outdoor black carbon from one of the test homes.

The effect of window opening on BC infiltration can clearly be seen from Figure 4. 7 (b). The outdoor BC concentration spike at 12 AM on 6/30/17 that lasted for at least one hour had no effect on the indoor BC concentration because the windows were closed during night. During daytime, however, the windows were left open and the indoor concentrations followed the outdoor profiles closely.

Similar to $PM_{2.5}$, all the BC time series data were analyzed to calculate the percentage of sampling times that outdoor concentrations were higher than indoors. The time fractions when outdoor BC concentrations were higher than indoors in the raw dataset were found to have a mean and standard deviation of 66% and 16%, respectively. Similarly, for the filtered dataset, the mean and standard deviation of time fractions of outdoor BC concentrations being higher than indoor BC concentrations were found to be 68% and 16%, respectively.

4.4.4.4 Carbon monoxide and Ozone

CO showed similar trends as PM and BC time series with few occasional indoor concentration spikes rising several times higher than usual. Two distinct features emerged from the raw CO time series data: 25 homes had the indoor and outdoor concentrations were roughly at the same level, and three homes which had higher average baseline level of CO. After a closer examination of the home appliance data, it was found that homes with higher indoor CO also had gas stoves. No systematic patterns were observed in outdoor CO concentrations with respect to plume density or road proximity, and outdoor CO was under 1 ppm always except during some notable spikes caused by local outdoor sources. No single hour was observed in any outdoor measurements of CO to continuously exceed the 1-hour averaged primary national ambient air quality standard (NAAQS) of 35 ppm.

O_3 profiles showed distinct outdoor diurnal patterns. The fraction of the time for which our outdoor samples collected in all homes exceeded the NAAQS of 70 ppb was found to be 6.45%.

4.4.4.5 Nitrogen dioxide

It was found that the homes with gas stoves had significantly high indoor NO_2 compared to outdoors (Figure 4. 8). This result is consistent with past studies [151,152]. These homes were not included in the data analysis for the investigation of outdoor NO_2 infiltration. In rest of the homes, indoor and outdoor concentrations of NO_2 were comparable to each other. The relatively high outdoor NO_2 concentration in home T429 was not relatable to the distance from the closest major road, leaving the only possible cause as a local source involving combustion (for example and idling vehicle or food grilling outdoors). In all cases, the concentrations of NO_2 were lower than the primary and secondary NAAQS of 53 ppb.

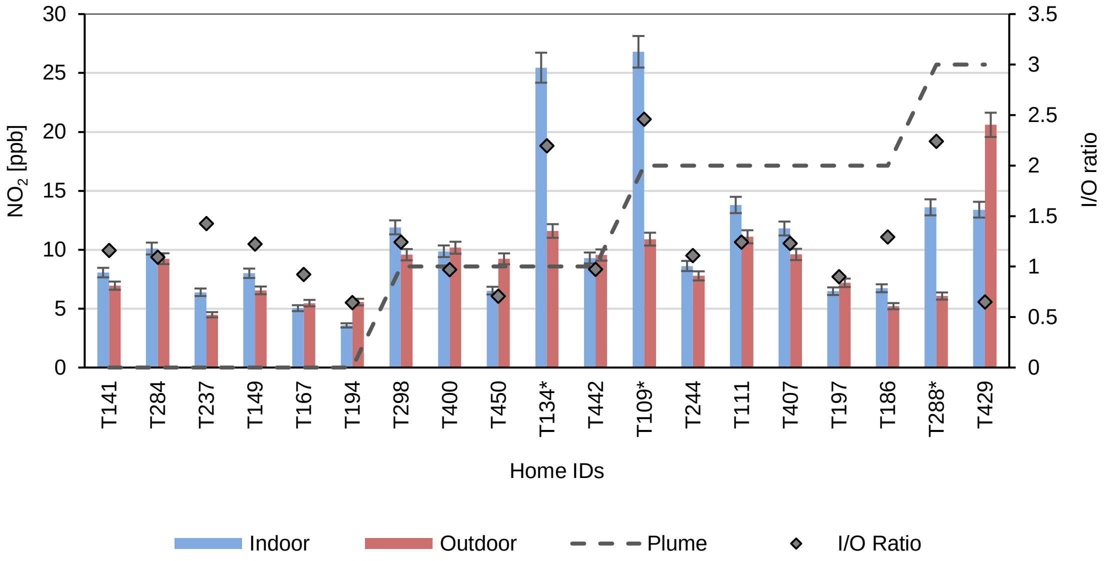


Figure 4. 8 NO$_2$ concentrations from all homes (n=19). Home IDs with asterisk represent homes with gas stoves. Error bars indicate sampler uncertainty. Homes are ordered from left to right according to the wildfire plume densities during sampling. The dashed line represents wildfire plume density categories (0,1, 2 and 3 values in the right side vertical axis as None, Low, Medium and High plume densities, respectively).

4.4.5 Impacts of road proximity

With respect to the distance to closest major road, outdoor PM$_{2.5}$, BC and NO$_2$ had the most significant difference among all pollutants for homes located closer to the roads (Figure 4. 9). Supplementary data also shows that indoor median PM$_{2.5}$ was 15% higher in homes located closer to the roads. the rate of increase of outdoor and indoor NO$_2$ concentrations were almost identical. Our results of the outdoor concentrations are in agreement with a past study using the same sampler [153]. O$_3$ is lower near roadways since it is titrated out of the atmosphere by the elevated NO$_2$ from the traffic, which is most likely why the maximum outdoor O$_3$ was lower in the homes nearer to roads [154,155].

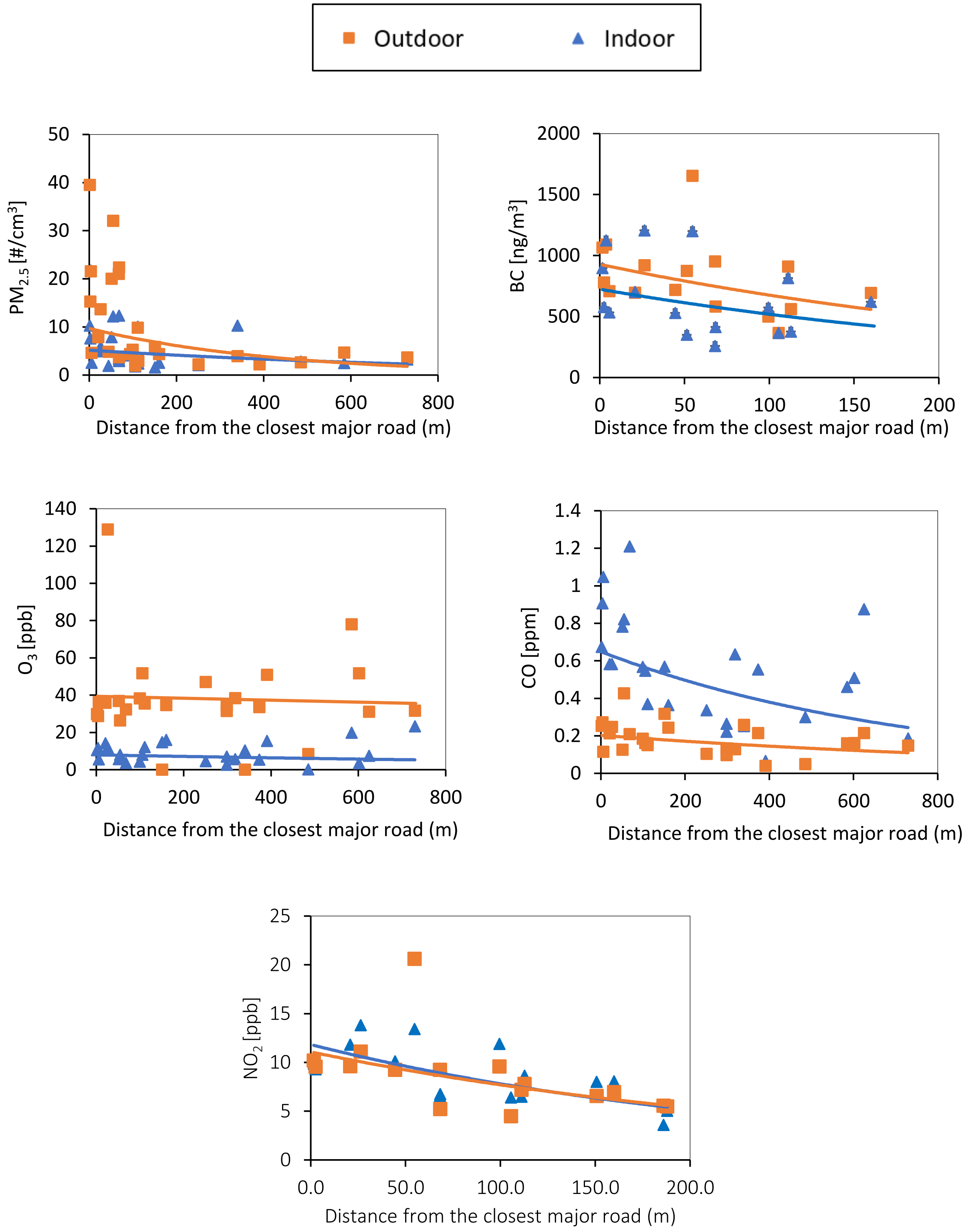


Figure 4. 9 Decreasing pollutant concentrations with increasing distance from the closest major road. This dataset does not include the homes with gas stoves. Error bars indicate measurement uncertainty of the samplers.

4.4.6 Effects of data filtering

One of the main objectives of this study was to investigate the impact of outdoor pollution on indoor air quality during wildfire seasons in Colorado. Data filtering was performed to remove the spikes in indoor concentrations of all the pollutants from indoor source or activity. The supplement section summarizes the pollutant datasets before and after data filtering. Corresponding Spearman's rank correlations (*r*) were also calculated between indoor and outdoor concentrations for both raw and filtered data. Filtering the data significantly changed the concentration distributions of all indoor pollutants. The percentage reduction in median indoor concentrations of $PM_{2.5}$, BC, CO and O_3 due to data filtration were 16%, 4%, 7% and 2.3%, respectively.

4.4.7 Indoor/outdoor ratios

Indoor/outdoor (I/O) ratio was identified as an effective metric for comparison of pollutant concentrations between indoors and outdoors. However, it should be noted that I/O ratio can decrease not just because of the decrease in indoor concentration, but also due to an increase in outdoor concentration (or a combination of both). Hence, it is important to also refer to the median indoor and outdoor concentrations to help elucidate associations. Median values are reported instead of arithmetic means because of their robustness towards outliers. The supplements section and Figure 4. 10 present the I/O ratios for all pollutants and the corresponding indoor and outdoor concentration medians and ranges to support the discussions. The I/O ratios and concentrations of all pollutants showed positively skewed but non-log-normal distribution (A-D test: $p<0.000$). Table S4. 5 summarizes the I/O ratios for all the pollutants according to various categories.

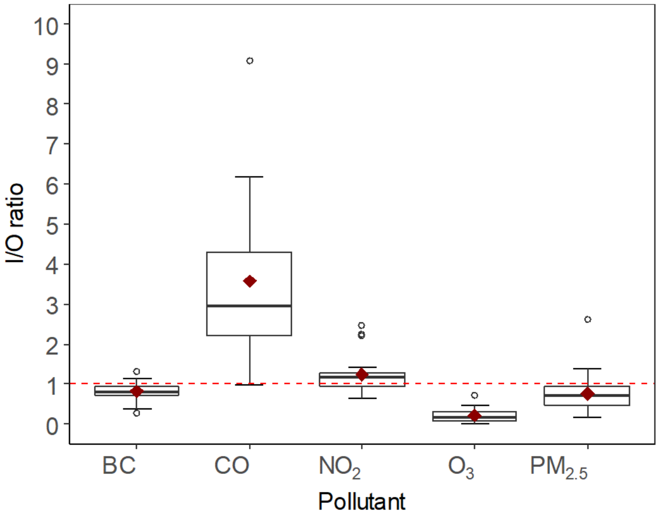


Figure 4. 10 Indoor/Outdoor ratios of all pollutants calculated from filtered datasets

Overall, median I/O ratio of CO and NO_2 were higher than one, whereas I/O ratio of $PM_{2.5}$, BC and O_3 were less than one in almost all cases. Median I/O ratio of CO suggested that indoor CO in all the homes were two to four times the outdoor concentrations. However, the median concentration of CO was lower than 1 ppm in all cases making it less concerning since human exhalation alone can contribute up to 1.5 ± 0.1 ppm or higher[156]. On the other hand, O_3 had I/O ratios less than 0.25 in all cases, which can be attributed to the reactivity of O_3 with indoor surfaces causing a decay from the indoor air.

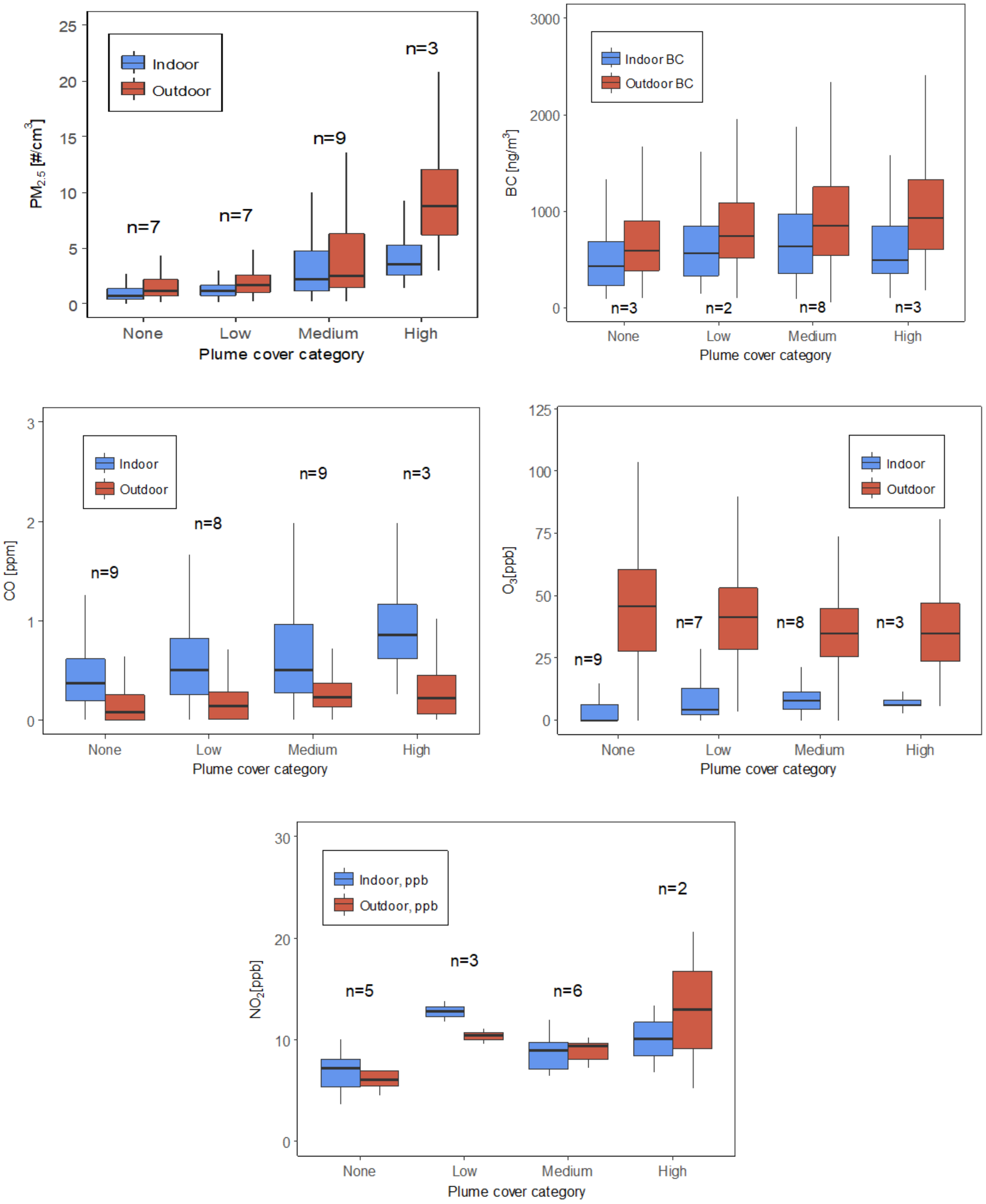


Figure 4. 11 Indoor and outdoor pollutant concentrations according to wildfire plume cover (filtered datasets). The mean differences were statistically significant for all pollutants except NO_2 (K-W test at α=0.05).

Wildfire plumes caused significant monotonic rise in the median outdoor as well as indoor concentrations of $PM_{2.5}$ (Figure 4. 11 and Table S4. 5). Outdoor Median $PM_{2.5}$ was 6.4 times higher and indoor median $PM_{2.5}$ was 3.6 times higher during the high plume cover compared to the times with no plume cover. The median increase in indoor $PM_{2.5}$ was 36% of the median increase in outdoor $PM_{2.5}$ between no plume cover and high plume cover categories. For BC however, although there was a monotonic rise in outdoor median concentrations with increasing wildfire plume density, indoor median BC concentration peaked at “medium” plume category and was lower for the “high” plume category than the “medium” category. I/O ratio was the highest for CO in the “high” plume category and was 35% higher than the “no plume” category. In the absence of any wildfire plumes, the reciprocal of I/O ratio (i.e. the O/I ratio) indicated that outdoor median concentrations of $PM_{2.5}$, BC and O_3 were 1.6, 1.4 and 5.9 times higher than indoors, respectively which can mostly be attributed to traffic related emissions in the absence of other significant local outdoor and indoor sources. However, the NO_2 I/O ratio was still higher than one even during no wildfire plume cover, and even when considering the dataset of homes with no gas stoves. This suggests that there can additional sources of NO_2 indoors, possibly the heating and combustion equipment like water heaters, furnaces, and gas fireplaces that have standing pilot lights even when they are not fully operational.

Location of the homes also significantly affected pollutant concentrations and I/O ratios. Homes built in the Aurora region had the lowest median I/O ratios for all pollutants except for CO, which was highest in Aurora. Detailed investigation of time series data revealed that one home in Boulder had a very short-term spike in the outdoor CO which lasted just a few minutes that caused the maximum reading in outdoor CO concentration to read as high as 14 ppm which was possibly caused due to an outdoor CO source like an idling vehicle close to the outdoor instrument rig.

Homes in West Denver and Central/North Denver regions had the highest maximum as well as median indoor and outdoor concentrations of $PM_{2.5}$ and BC. Homes in West Denver and Central/North Denver regions also had the highest I/O ratios for O_3.

According to building type, EER homes had the lowest median I/O ratios for all the pollutants. This is most likely due to location, since non-EER homes were generally located in places with higher outdoor median pollutant concentrations in all cases except O_3. As a result, the indoor median concentrations of all the pollutants except O_3 were also high indoors.

With respect to mechanical ventilation (MV), it was seen that the median I/O ratio of $PM_{2.5,}$ BC and O_3 were higher by 18%, 4%, and 5% respectively when MV was present. Median I/O ratio of CO was lower in homes with MV by 3%.

The time-activity diary revealed that most occupants left at least one window open for 24 hours a day. Indoor median BC concentration had a monotonic rise with the number of hours of at least one window open in the house (Figure 4. 12). However, similar monotonic rise was not seen with $PM_{2.5}$. Window opening also had a significant impact on the I/O ratio of CO, with the highest I/O ratio for the homes which had all the windows closed throughout the sampling period, which was roughly three times higher than having the window open for even a small fraction of the time. Indoor median O_3 was found to increase with increasing time span of the windows being open, which was expected since O_3 is known to react with indoor surfaces and decay rapidly. Even in most homes where the window was left open for more than 12 hours, indoor O_3 was one-quarter of the outdoor level.

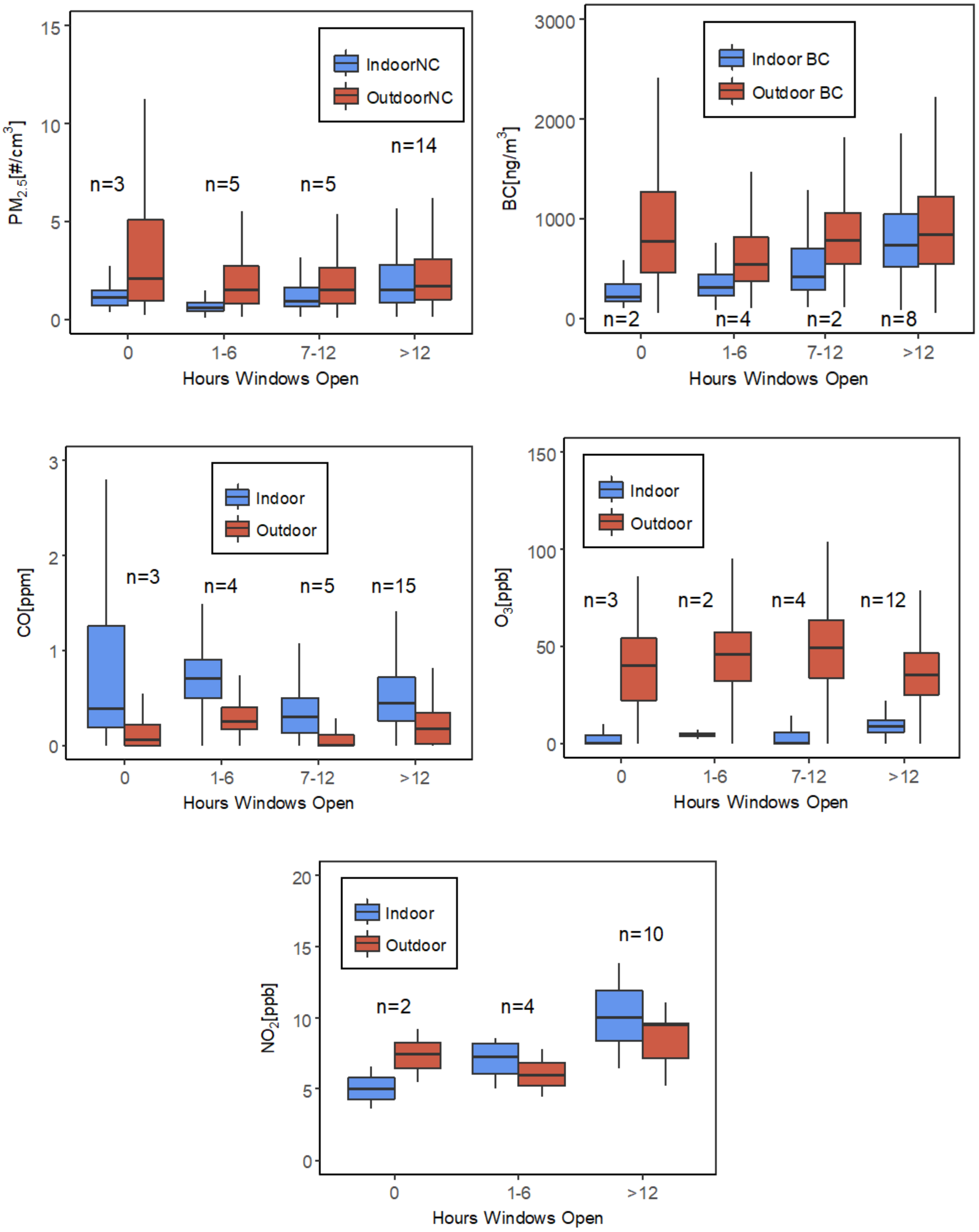


Figure 4. 12 Indoor and outdoor pollutant concentrations according to the hours of window opening (filtered dataset). The mean differences were statistically significant for all pollutants except for NO_2 (K-W test at α=0.05).

4.5 Conclusion

Outdoor air pollution related to traffic emissions and wildfires were found to significantly affect the indoor air pollutant concentrations due to infiltration and natural ventilation in low-income homes. Wildfires were a significant source of indoor $PM_{2.5}$. I/O ratios of CO were found to be consistently two to three times higher than other pollutants measured. Outdoor $PM_{2.5}$ and BC concentration were found to be higher than indoors for more than 60% of the time. Window opening time lengths were also found to significantly affect the inflow of outdoor BC and the indoor concentration of CO. Indoor NO_2 concentrations were found to be significantly higher compared to outdoors in the homes with gas stoves.

Indoor sources caused peaks in indoor pollutant concentrations. Indoor source-related emissions should be addressed with engineering approaches such as source control (stove exhaust hoods) or other strategies to reduce exposures. The building envelope is usually thought of as the protective layer between the indoor environment and outdoor air pollution. Even when staying indoors with no significant indoor sources, indoor concentrations of $PM_{2.5}$ can be elevated by up to three times during wildfire plumes compared to normal levels.

MV systems causing a significant increase in $PM_{2.5}$ and a slight increase of other pollutants is another major concern, which signifies that during the wildfire seasons, MV installations may not be well serving the purpose of their installation in the first place. Most of the mechanical ventilation systems currently prevalent in residential settings (and all the ones in our study) are of the exhaust type and with constant airflow settings for all seasons that subsequently rely on infiltration pathways for the make-up ventilation air. One possibility to improve ventilation air supply with an MV system is to install MV on the supply side rather than the exhaust side, and with an intake air filtration media. The positive pressure maintained indoors by such a system can also reduce infiltration rates and mitigate potential combustion exhaust backdrafts. The use of heat recovery ventilation (HRV) or energy recovery ventilation (ERV) systems is another option which can provide greater energy efficiency in addition to air filtration.

4.6 Acknowledgement

This work was supported by the Environment Protection Agency (EPA-G2014-STAR-A1, Miller). The authors would like to thank Xcel Energy and Boulder Housing Partners for their genuine support, all the participating households, the advisory board and the research assistants: Hanadi Salamah, Maia Lenz, Tess Bloom, Ryan Hourigan, Sarah Hong, Eduardo Soderberg and Adam Hester. The authors are also thankful to the Hannigan Lab at CU Boulder for their genuine support, especially from Evan Coffey, Drew Meyers and Ricardo Piedrahita, and to Prof. John Volkens from Colorado State University for the help with instrumentation.

4.7 Supplemental materials

Supplement S4 A: Figures and Tables

Figure S4. 1 Outdoor instrument rig (Left) and Indoor Instrument rig (Right). [Legend for labels: 1=Weather station; 2= Dylos- 1700 Monitor (outdoor instrument covered with metallic bucket); 3=microAeth AE51 Aethalometer (outdoor instrument covered with metallic bucket); 4=Y-pod; 5=Ogawa NO2 passive sampler; 6=weather-protected electrical connection point; 7=tripod stand.]

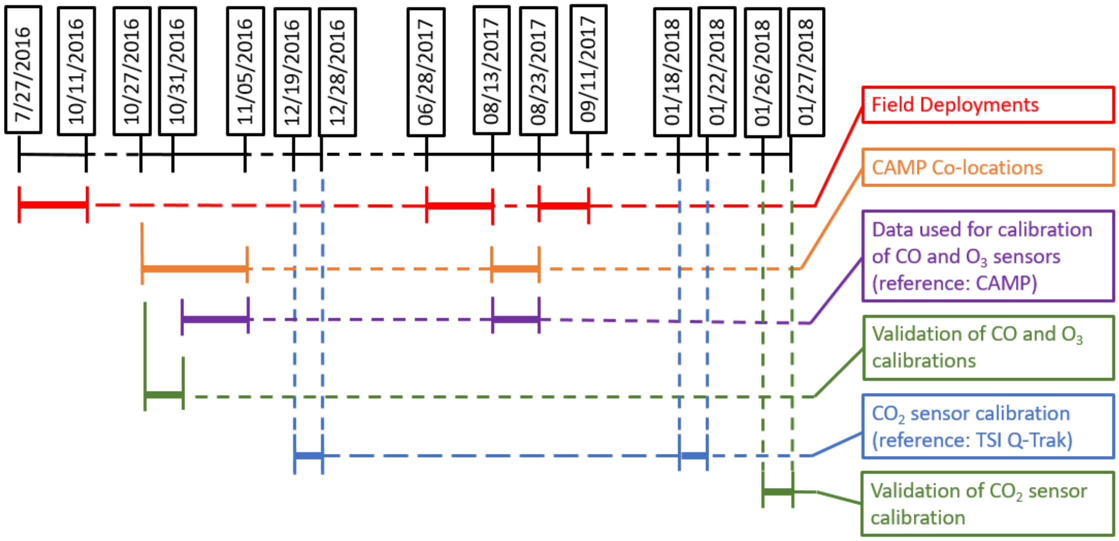
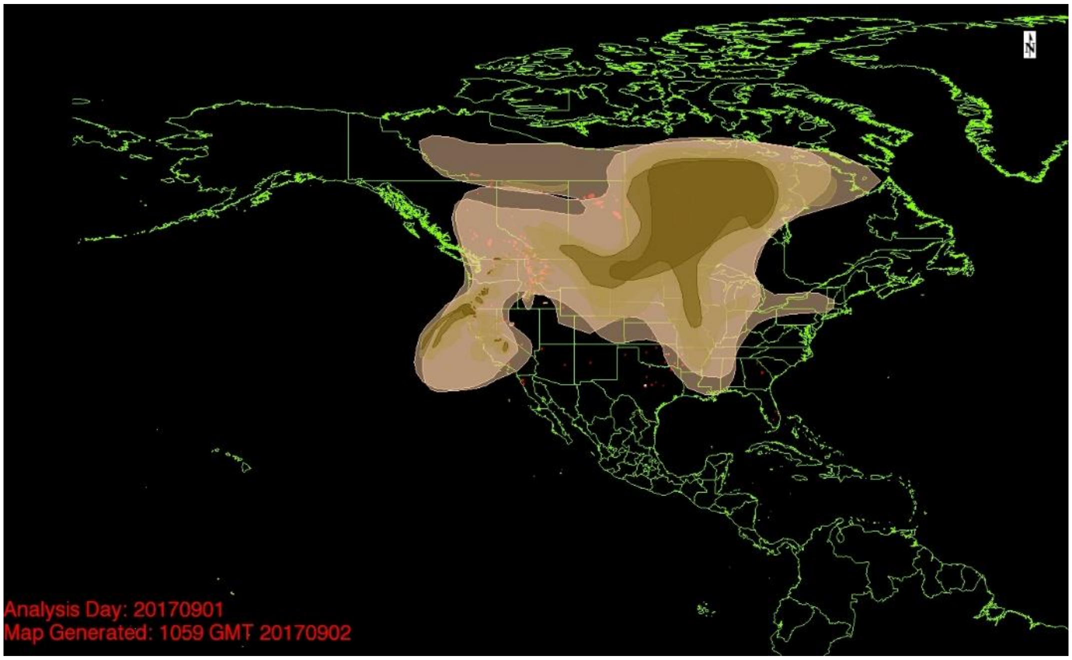
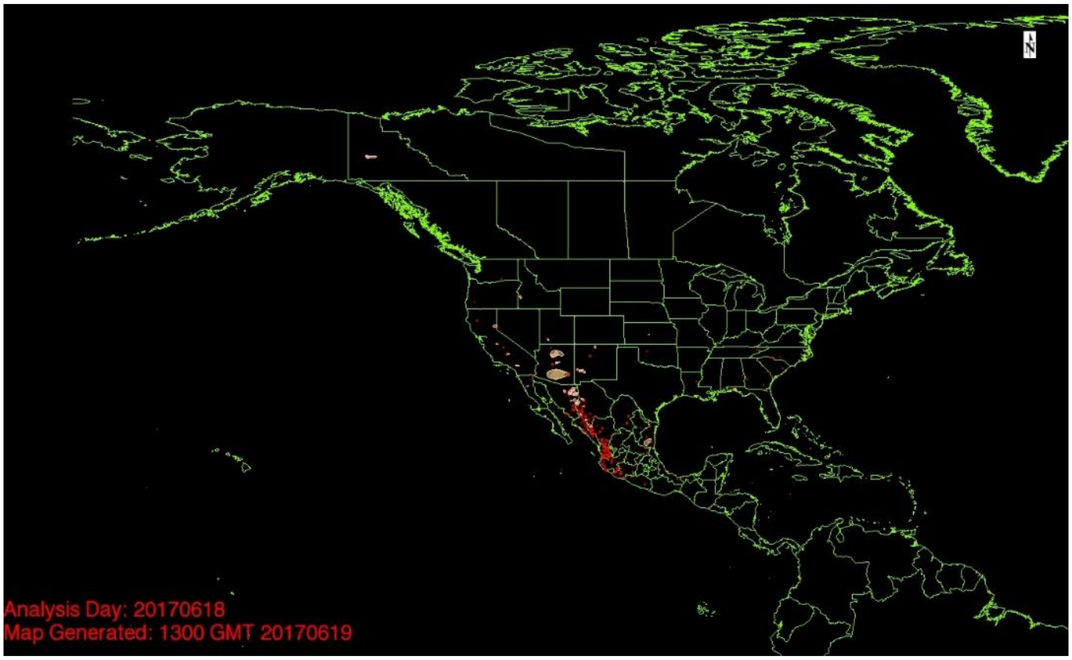


Figure S4. 2 Schematic showing timeline of instrument deployment periods, sensor calibration periods for Y-Pods and validation periods for sensor calibrations. CO2 data was calibrated using TSI Q-Trak as the reference instrument, but the data showed poor results during validation and hence CO2 data was discarded.



(a)



(b)

Figure S4. 3 Example of NOAA HMS remote sensing data showing a day with plume cover (a) and no plume cover (b) over the state of Colorado

Table S4. 1 Summary crosstabs of sample sizes, and distributions of AAER and ACH50 across major housing characteristics and sources that impact indoor air quality

Categories	Counts (% of total) Total N = 28 (100%)*	AAER [hr^{-1}] Median (Range)	p-value*	ACH50 [hr^{-1}] Median (Range)	p-value**
AAER summary					
Overall AAER of all homes	28 (100)	0.48 (0.22-1.3)	-	8.4 (4.1-22)	-
Location					
Aurora	4 (14)	0.49 (0.22-0.65)	0.71	8.8 (4.9-11)	0.68
Boulder/Longmont	9 (32)	0.47 (0.27-0.86)		8.4 (4.1-11)	
West Denver	11 (39)	0.50 (0.34-1.3)		8.5 (6.3-22)	
Central/North Denver	4 (14)	0.47 (0.28-1.2)		7.9 (4.9-22)	
Home Type					
Built Green (BG)	5 (18)	0.48 (0.33-0.86)	0.81	9.0 (6.7-11)	0.77
Energy efficiency retrofitted (EER)	13 (46)	0.47 (0.22-1.3)		8.0 (4.1-22)	
Conventional (Non-EER)	10 (36)	0.47 (0.27-1.2)		9.0 (5.6-22)	
Proximity to the closest major road [a]					
< 200 m	15 (54)	0.39 (0.22-1.1)	0.12	7.5 (4.1-20)	0.13
> 200 m	13 (46)	0.50 (0.28-1.3)		9.7 (4.9-22)	
Wildfire smoke plume cover density in the study region [b]					
None = no wildfire plume cover	10 (36)	0.43 (0.33-0.65)	0.27	7.3 (4.1-11)	0.20
Low = low density (≤ 6 $\mu g/m^3$)	7 (25)	0.50 (0.37-0.62)		9.8 (6.7-11)	
Medium = medium density (≤ 15 $\mu g/m^3$)	9 (32)	0.51 (0.22-1.3)		8.4 (4.9-22)	
High = high density (≤ 27 $\mu g/m^3$)	3 (11)	0.61 (0.35-0.86)		11 (6.0-11)	
Mechanical Ventilation					
Mechanical ventilation installed [c]	5 (18)	0.47 (0.33-0.86)	0.92	6.7 (4.1-11)	0.23
No mechanical ventilation	23 (82)	0.49 (0.22-1.3)		8.5 (4.9-22)	

AAER=Annual-average Air Exchange Rate; ACH50=Air Changer per Hour at 50 Pa; BG= Built Green; EER= Energy Efficiency Retrofitted

[*] p-values for one-way ANOVA for comparison of mean ln(AAER) between groups

[**] p-values for one-way ANOVA for comparison of mean ln(ACH50) between groups

[a] Average annual daily traffic (AADT >10,000)

[b] According to NOAA HMS satellite imagery

[c] Three out of the five MV systems were heat recover ventilation (HRV) systems which was intermittent in operation whereas the remaining two were continuous MV systems. AAER adjustments were only made to the continuous MV systems

Table S4. 2 Concentration comparisons between indoor and outdoor pollutants before and after data filtration.

	Concentrations Median (Range)		
	Raw data	Filtered data	p_2-value[c]
$PM_{2.5}$ [#/cm^3]			
Indoor	1.40 (0-203)	1.17 (0.0494-199)	<0.000
Outdoor	1.66 (0.0850-79.1)	1.69 (0.0850-79.1)	<0.000
r_s[a]	0.311	0.374	
p_1-value [b]	<0.000	<0.000	
BC [ng/m^3]			
Indoor	532 (82.2-15900)	512 (82.2-5081)	<0.000
Outdoor	768 (54.5-39100)	766 (54.5-39100)	0.629
r_s	0.507	0.525	
p_1-value	<0.000	<0.000	
CO [ppm]			
Indoor	0.485 (0-28.2)	0.450 (0-10.5)	<0.000
Outdoor	0.150 (0-14.9)	0.144 (0-14.0)	0.000467
r_s	0.434	0.252	
p_1-value	<0.000	<0.000	
O_3 [ppb]			
Indoor	5.12 (0-72.5)	5.0 (0-72.5)	0.000109
Outdoor	39.7 (0-**)	39.5 (0-106)	0.119
r_s	0.0323	0.110	
p_1-value	0.345	0.0373	

[a] Spearman's rank correlation coefficient between indoor and outdoor medians

[b] p-values for K-W test between indoor and outdoor medians

[c] p-values for Wilcoxon Mann-Whitney (U) test between raw and filtered dataset medians (K-W test could not be performed due to different lengths of datasets)

** High value signifying outlier

Table S4. 3 Cross-tabulation of indoor and outdoor temperature and relative humidity with various home characteristics (raw dataset). Total N=28.

	n (% of total)	Temperature (ºC)		Relative Humidity (%)	
		Indoor Median(Range) / Outdoor Median (Range)	I/O ratio	Indoor Median(Range) / Outdoor Median (Range)	I/O ratio
Location					
Aurora	4 (14.3)	27.3 (21.2-33.8) / 23.5 (10.9-46.8)	1.16	34.92 (25.3-46.4) / 41.6 (9.22-81.9)	0.84
Boulder/ Longmont	9 (32.1)	23.2 (18.9-30.2) / 16.8 (1.4-41.1)	1.38	30.9 (13.7-55.0) / 35.3 (9.10-88.5)	0.87
West Denver	11 (39.3)	26.4 (17.1-34.0) / 21.4 (1.70-45.7)	1.23	34.8 (14.6-61.2) / 37.7 (6.57-86.0)	0.92
Central/North Denver	4 (14.3)	26.4 (19.7-30.0) / 20.9 (9.79-44.4)	1.26	34.1 (19.7-60.0) / 42.5 (7.11-84.4)	0.80
Building Type†					
BG	5 (17.9)	22.4 (18.9-30.16) / 12.9 (1.4-39.1)	1.74	26.6 (13.7-46.7) / 29.4 (9.10-83.2)	0.90
EER	13 (46.4)	27.1 (17.1-34.0) / 22.2 (1.69-46.8)	1.22	34.6 (14.6-55.0) / 39.9 (6.57-88.5)	0.87
Non-EER	10 (35.7)	25.7 (19.74-31.1) / 21.6 (9.79-44.4)	1.19	40.6 (14.8-61.7) / 43.1 (7.11-86.0)	0.94
Road Proximity					
<100 m	15 (53.6)	25.3 (19.5-33.8) / 19.6 (1.56-44.4)	1.29	34.1 (14.5-61.7) / 39.4 (7.11-86.0)	0.86
100-200 m	7 (25.0)	26.7 (17.1-34.4) / 22.6 (1.69-46.8)	1.18	35.2 (15.3-55.0) / 39.1 (7.54-88.5)	0.90
>200 m	6 (21.4)	25.4 (19.0-32.2) / 17.8 (1.4-44.8)	1.43	31.1 (13.7-44.0) / 34.9 (6.57-83.5)	0.89
Wildfire Plume Density					
None	10 (35.7)	22.7 (17.1-34.0) / 16.5 (1.40-46.7)	1.37	31.1 (13.7-55.0) / 34.5 (9.10-88.5)	0.90
Low	6 (21.4)	26.7 (19.8-32.0) / 22.8 (9.79-45.7)	1.17	36.7 (14.7-59.8) / 40.1 (6.62-84.4)	0.91
Medium	9 (32.1)	26.5 (20.1-32.2) / 21.6 (10.6-44.7)	1.23	36.8 (14.6-61.7) / 41.8 (6.57-86.0)	0.88
High	3 (10.7)	24.5 (21.2-29.5) / 21.5 (10.9-39.1)	1.14	40.4 (22.9-46.7) / 35.5 (9.26-71.1)	1.14
Mechanical Ventilation					
Present	5 (17.9)	23.5 (19.5-34.0) / 17.8 (1.56-44.7)	1.32	28.5 (14.5-47.5) / 36.9 (10.3-88.5)	0.77
Absent	23 (82.1)	26.0 (17.1-33.8) / 20.5 (1.40-46.8)	1.27	34.7 (13.7-61.7) / 38.1 (6.57-86.0)	0.91
Hours Windows Open					
0	3 (10.7)	24.7 (19.9-28.3) / 18.4 (1.56-40.9)	1.34	31.7 (16.1-44.3) / 44.8 (12.9-88.5)	0.71
1-6	4 (14.3)	26.0 (17.1-33.0) / 21.4 (1.69-46.8)	1.21	34.0 (15.3-55.0) / 36.1 (7.54-84.4)	0.94
7-12	5 (17.9)	22.8 (19.0-29.5) / 16.8 (2.64-41.5)	1.36	32.6 (13.7-53.9) / 36.4 (9.10-83.5)	0.89

>12	16 (57.1)	26.2 (19.0-34.0) / 21.4 (1.40-44.8)	1.22	34.6 (14.6-61.7) / 38.1 (6.57-86.0)	0.91
Gas Stoves					
Present	5 (17.9)	26.0 (19.8-31.0) / 21.1 (9.79-42.0)	1.23	40.8 (14.8-61.7) / 41.2 (7.11-86.0)	0.99
Absent	23 (82.1)	25.6 (17.1-34.0) / 19.7 (1.40-46.8)	1.30	33.4 (13.7-55.0) / 37.5 (6.57-88.5)	0.89
Stove Hood Types					
Exhaust	8 (28.6)	23.9 (17.1-29.5) / 17.6 (1.56-41.1)	1.36	34.0 (15.3-52.1) / 41.0 (9.07-84.4)	0.83
Recirculating	13 (46.4)	25.7 (18.9-34.0) / 20.4 (1.4-46.75)	1.26	34.4 (13.7-61.7) / 35.3 (6.62-86.0)	0.97
Absent	7 (25.0)	27.1 (19.7-32.2) / 21.5 (9.79-44.7)	1.26	32.6 (14.6-59.9) / 39.8 (6.57-88.5)	0.82

[†] BG=Built Green; EER= Energy Efficiency Retrofitted; Non-EER=Non-Energy Efficiency Retrofitted (conventional homes as a control group)

I/O ratios across all categories were statistically significant at α=0.05 (K-W test)

Table S4. 4 Pollutant concentrations indoors and outdoors from raw datasets with the corresponding p-values from K-W test on I/O ratios between categories

	Concentrations: Indoor Median (Indoor Range) / Outdoor Median (Outdoor Range)									
	$PM_{2.5}$ [#/cm^3]	n/ **(I/O†)**	BC [ng/m^3]	n/ **(I/O)**	CO [ppm]	n/ **(I/O)**	O_3 [ppb]	n/ **(I/O)**	NO_2 [ppb]*	n/ **(I/O)**
Location										
Aurora	0.992 (0.237-29.4)/ 2.47 (0.275-58.1)	4/ **0.40**	387 (109-3490)/ 739 (54.5-39100)	4/ **0.52**	0.823 (0.04-2.95)/ 0.169 (0-1.75)	4/ **4.87**	5.35 (0-41.6)/ 36.8 (0-**)	4/ **0.14**	8.31 (6.39-13.6)/ 7.65 (4.48-9.24)	4/ 1.08
Boulder/ Longmont	1.30 (0.0989-201)/ 1.16 (0.0848-78.7)	7/ **1.12**	446 (82.3-15900)/ 652 (122-11000)	4/ **0.68**	0.307 (0-10.4)/ 0 (0-14.0)	9/ **-**	0 (0-72.5)/ 48.2 (0-103)	6/ **0.0**	5.76 (3.58-6.73)/ 5.52 (5.21-7.19)	4/ 1.04
West Denver	1.38 (0.0494-199)/ 1.75 (0.159-79.1)	11/ **0.79**	672 (119-8200)/ 791 (57.9-16300)	8/ **0.85**	0.540 (0-28.2)/ 0.239 (0-14.9)	11/ **2.26**	8.44 (0-64.0)/ 37.6 (0-105)	9/ **0.22**	11.9 (8.00-26.8)/ 9.89 (6.55-11.6)	8/ 1.20
Central/ North Denver	2.10 (0-203)/ 2.38 (0.275-35.6)	4/ **0.88**	640 (83.3-14300)/ 957 (128-17700)	3/ **0.67**	0.724 (0.06-12.9)/ 0.206 (0-2.80)	3/ **3.51**	7.80 (4.18-16.9)/ 29.7 (5.50-75.3)	2/ **0.26**	9.30 (8.62-13.4)/ 9.55 (7.78-20.6)	3/ 0.97
p-values:		<0.01		<0.01		<0.01		<0.01		0.14
Building Type										
BG [a]	1.41 (1.41)/ 1.03 (0.0847-78.7)	5/ **1.37**	480 (98.3-15900)/ 590 (176-3760)	1/ **0.81**	0.239 (0-4.46)/ 0 (0-5.54)	5/ **-**	0 (0-72.5)/ 53.2 (0-104)	4/ **0.0**	6.73 (6.73-6.73)/ 5.21 (5.21-5.21)	1/ 1.29
EER [b]	0.982 (0.494-199)/ 1.54 (0.159-79.1)	11/ **0.64**	383 (82.3-8210)/ 629 (54.5-39100)	10/ **0.61**	0.554 (0-28.2)/ 0.209 (0-14.0)	13/ **2.65**	4.80 (0-63.9)/ 38.1 (0-**)	9/ **0.13**	8.03 (3.58-26.8)/ 7.37 (4.48-10.9)	10/ 1.09
Non-EER[c]	2.57 (0-203)/ 3.23 (0.275-59.2)	10/ **0.79**	808 (83.3-14300)/ 961 (128-21500)	8/ **0.84**	0.707 (0-12.9)/ 0.217 (0-14.9)	9/ **3.25**	9.11 (0-44.1)/ 33.2 (5.50-95.8)	8/ **0.27**	12.6 (6.48-25.5)/ 9.89 (6.07-20.6)	8/ 1.27
p-values:		<0.01		<0.01		<0.01		<0.01		0.64
Road Proximity										
<100 m	2.00 (0-203)/ 2.40 (0.131-78.7)	15/ **0.83**	664 (83.3-15900)/ 872 (54.5-39100)	12/ **0.76**	0.584 (0-12.8)/ 0.134 (0-14.9)	15/ **4.35**	4.94 (0-42.0)/ 38.0 (0-104)	13/ **0.13**	11.8 (6.53-26.8)/ 9.59 (5.21-20.6)	12/ 1.23
100-200 m	0.801 (0.0494-45.0)/ 1.68 (0.159-79.1)	5/ **0.48**	390 (82.3-6360)/ 612 (97.0-11000)	7/ **0.64**	0.646 (0-4.91)/ 0.244 (0-7.88)	7/ **2.65**	6.16 (1.78-59.5)/ 39.2 (0-**)	5/ **0.16**	6.48 (3.58-8.62)/ 6.55 (4.48-7.78)	7/ 0.99
>200 m	1.17 (0.0989-199)/ 1.21 (0.0848-66.7)	6/ **0.97**	- -	0	0.232 (0-28.2)/ 0.006 (0-14.0)	5/ **38.67**	0 (0-72.5)/ 49.0 (0.22-95.8)	3/ **0.0**	- -	0
p-values:		<0.01		<0.01		<0.01		<0.01		0.24

	Concentrations: Indoor Median (Indoor Range) / Outdoor Median (Outdoor Range)									
	PM$_{2.5}$ [#/cm^3]	n/ **(I/O†)**	BC [ng/m^3]	n/ **(I/O)**	CO [ppm]	n/ **(I/O)**	O$_3$ [ppb]	n/ **(I/O)**	NO$_2$ [ppb]*	n/ **(I/O)**
Wildfire Plume Density										
None	0.897 (0.494-160)/ 1.10 (0.0848-79.1)	7/ **0.81**	424 (82.2-6360)/ 589 (98.3-6900)	5/ **0.72**	0.378 (0-3.23)/ 0.0755 (0-7.87)	9/ **5.01**	0 (0-72.5)/ 45.6 (0-**)	7/ **0.0**	7.19 (3.58-10.1)/ 6.06 (4.48-9.24)	6/ 1.18
Low	1.34 (0-203)/ 1.67 (0.229-66.7)	7/ **0.80**	568 (144-4700)/ 745 (97.0-8280)	3/ **0.76**	0.554 (0-12.8)/ 0.140 (0-14.9)	7/ **3.96**	4.41 (0-64.0)/ 41.2 (3.19)	4/ **0.11**	9.87 (6.53-25.5)/ 9.58 (9.23-11.6)	5/ 1.03
Medium	2.54 (0.251-199)/ 2.39 (0.265-59.2)	9/ **1.06**	644 (83.3-12100)/ 859 (54.5-39100)	8/ **0.75**	0.618 (0-28.2)/ 0.229 (0-1.90)	8/ **2.70**	7.69 (0-41.2)/ 34.5 (0-81.7)	7/ **0.22**	10.2 (6.48-26.8)/ 8.69 (5.21-11.1)	6/ 1.17
High	5.32 (1.36-201)/ 6.67 (1.01-58.1)	3/ **0.80**	540 (98.3-15900)/ 946 (176-21500)	3/ **0.57**	0.88 (0.26-4.46)/ 0.213 (0-2.80)	3/ **4.13**	6.18 (2.68-11.3)/ 34.5 (5.50-80.5)	3/ **0.18**	13.5 (13.4-13.6)/ 13.3 (6.07-20.6)	2/ 1.01
p-values:		<0.01		<0.01		<0.01		<0.01		0.70
Mechanical Ventilation										
Present	1.30 (0.198-201)/ 1.30 (0.131-78.7)	4/ **1.00**	480 (98.3-15900)/ 623 (98.3-6290)	3/ **0.77**	0.333 (0-4.46)/ 0.0258 (0-7.88)	5/ **12.8**	0 (0-59.5)/ 44.2 (0-103)	5/ **0.0**	6.73 (3.58-8.06)/ 5.56 (5.21-6.95)	3/ 1.21
Absent	1.43 (0-203)/ 1.75 (0.0847-79.1)	22/ **0.82**	557 (82.2-14300)/ 793 (54.5-39100)	16/ **0.70**	0.539 (0-28.2)/ 0.173 (0-14.9)	22/ **3.11**	6.1 (0-72.5)/ 38.3 (0-**)	16/ **0.16**	9.99 (5.04-26.8)/ 9.40 (4.48-20.6)	16/ 1.06
p-values:		<0.01		<0.01		<0.01		<0.01		0.65
Hours Windows Open										
0	1.19 (0.314-36.8)/ 1.57 (0.131-54.0)	3/ **0.76**	250 (98.9-6360)/ 740 (54.4-39100)	2/ **0.34**	0.466 (0-3.23)/ 0.0742 (0-7.88)	3/ **6.28**	0 (0-20.5)/ 40.2 (0-85.7)	3/ **0.0**	5.06 (3.58-6.53)/ 7.40 (5.56-9.23)	2/ **0.68**
1- 6	0.611 (0.05-20.9)/ 1.50 (0.159-79.1)	4/ **0.41**	316 (82.2-2120)/ 540 (97.0-6950)	4/ **0.58**	0.713 (0-4.91)/ 0.252 (0-3.01)	4/ **2.83**	4.58 (1.78-41.6)/ 46.7 (0-**)	2/ **0.10**	7.20 (5.04-8.62)/ 6.01 (4.48-7.78)	4/ **1.20**
7-12	1.24 (0.0989-160)/ 1.41 (0.0848-78.7)	5/ **0.88**	406 (109-3000)/ 800 (119-21500)	2/ **0.51**	0.322 (0-10.5)/ 0 (0-14.0)	5/ **-**	0 (0-72.5)/ 49.4 (0-104)	4/ **0.0**	20.2 (13.6-26.8)/ 8.48 (6.07-10.9)	2/ **2.38**
> 12	1.80 (0-203)/ 1.82 (0.120-59.2)	14/ **0.99**	761 (83.3-15900)/ 860 (58.0-17800)	11/ **0.88**	0.477 (0-28.2)/ 0.179 (0-14.9)	15/ **2.66**	8.82 (0-64.0)/ 35.2 (0-95.8)	12/ **0.25**	10.1 (6.48-25.5)/ 9.58 (5.21-20.6)	11/ **1.05**
p-values:		<0.01		<0.01		<0.01		<0.01		0.035

	Concentrations: Indoor Median (Indoor Range) / Outdoor Median (Outdoor Range)									
	$PM_{2.5}$ [#/cm^3]	n/ (**I/O**†)	BC [ng/m^3]	n/ (**I/O**)	CO [ppm]	n/ (**I/O**)	O_3 [ppb]	n/ (**I/O**)	NO_2 [ppb]*	n/ (**I/O**)
Gas Stoves										
Present	1.65 (0-203)/ 1.97 (0.275-59.2)	5/ **0.84**	597 (109-4400)/ 858 (119-21500)	3/ **0.70**	0.736 (0-12.9)/ 0.142 (0-1.23)	4/ **5.18**	6.00 (0-44.2)/ 36.1 (6.44-95.8)	4/ **0.17**	25.5 (13.6-26.8)/ 10.9 (6.07-11.6)	3/ **2.34**
Absent	1.33 (0.0494-201)/ 1.58 (0.0848-79.1)	21/ **0.84**	522 (82.2-15900)/ 748 (54.5-39100)	16/ **0.70**	0.435 (0-28.2)/ 0.151 (0-14.9)	23/ **2.88**	4.55 (0-72.5)/ 40.8 (0-**)	17/ **0.11**	8.34 (3.58-13.8)/ 8.51 (4.48-20.6)	16/ **0.98**
p-values:		<0.01		<0.01		<0.01		<0.01		0.007
Stove Hood Types										
Exhaust	1.18 (0.0494-201)/ 2.40 (0.131-79.1)	8/ **0.49**	499 (98.3-15900)/ 827 (54.4-39100)	5/ **0.60**	0.478 (0-10.4)/ 0.160 (0-14.0)	8/ **2.99**	3.93 (0-42.0)/ 39.5 (0-85.7)	6/ **0.10**	6.73 (6.48-13.6)/ 7.19 (5.21-9.60)	5/ 0.94
Recirculating	1.31 (0.0989-160)/ 1.27 (0.0848-78.7)	12/ **1.03**	495 (82.2-12100)/ 695 (97.0-16200)	10/ **0.71**	0.427 (0-7.33)/ 0.0628 (0-14.9)	12/ **6.80**	4.97 (0-72.5)/ 41.8 (0-**)	10/ **0.12**	8.96 (5.04-26.8)/ 8.51 (4.48-11.6)	10/ 1.05
Absent	1.85 (0-203)/ 1.75 (0.265-53.1)	6/ **1.06**	713 (98.9-14300)/ 904 (58.0-17800)	4/ **0.79**	0.616 (0-28.2)/ 0.231 (0-7.88)	7/ **2.67**	7.61 (0-44.1)/ 33.9 (0-95.6)	5/ **0.22**	10.9 (3.58-13.4)/ 9.88 (5.56-20.6)	4/ 1.10
p-values:		<0.01		<0.01		<0.01		<0.01		0.18

[*] NO_2 concentrations were TWA measurements, all other pollutants were time resolved (one-minute resolution)

[a] BG=Built Green; [b] EER=Energy Efficiency Retrofitted; [c] Non-EER=Non-Energy Efficiency Retrofitted (conventional homes as a control group)

** High value indicating data outlier

[†] I/O ratios that showed statistical significance (K-W test) in the mean differences (p<0.05) are shown in bold

Table S4. 5 Pollutant concentrations indoors and outdoors from filtered datasets with the corresponding p-values from K-W test on I/O ratios between categories

	Concentrations: Indoor Median (Indoor Range) / Outdoor Median (Outdoor Range)									
	$PM_{2.5}$ [#/cm^3]	n/ **(I/O)**	BC [ng/m^3]	n/ **(I/O)**	CO [ppm]	n/ **(I/O)**	O_3 [ppb]	n/ **(I/O)**	NO_2 [ppb]*	n/ **(I/O)**
Location										
Aurora	2.54 (0.680-26.2)/ 6.13 (0.780-165)	4/ **0.41**	386 (109-3490)/ 739 (54.5-39100)	4/ **0.52**	0.790(0-2.95)/ 0.185 (0-1.75)	4/ **4.27**	5.12(0.475-10.4)/ 36.4 (0.796-80.5)	4/ **0.14**	6.53 (6.39-10.1)/ 9.23 (4.48-9.24)	3/ 0.71
Boulder/ Longmont	2.88(0.280-44.8)/ 3.42(0.240-111)	7/ **0.84**	409 (82.3-4460)/ 657 (122-11000)	4/ **0.62**	0.458 (0-10.5)/ 0.156 (0-14.0)	9/ **2.94**	7.55 (0-72.5)/ 44.8 (0.225-92.5)	6/ **0.17**	5.76 (3.58-6.73)/ 9.59 (5.21-7.19)	4/ 0.60
West Denver	3.35(0.140-563)/ 5.06(0.450-224)	11/ **0.66**	664 (119-4700)/ 787 (57.9-16300)	8/ **0.84**	0.537 (0-5.3)/ 0.274 (0-3.45)	11/ **1.96**	9.26 (0-64.0)/ 38.2 (0.152-106)	9/ **0.24**	10.8 (8.00-13.8)/ 9.89 (6.55-11.1)	6/ 1.1
Central/ North Denver	5.20(0.790-34.8)/ 7.14(0.780-101)	4/ **0.73**	599 (83.3-5080)/ 943 (128-17800)	3/ **0.64**	0.73 (0-2.18)/ 0.279 (0-2.80)	3/ **2.62**	7.80 (4.19-16.9)/ 29.7 (5.50-75.3)	2/ **0.26**	9.30 (8.62-13.4)/ 9.55 (7.78-20.6)	3/ 0.97
p-values:		<0.01		<0.01		<0.01		<0.01		0.33
Building Type										
BG [a]	2.99(0.280-44.8)/ 2.92(0.240-111)	5/ **1.02**	434 (98.3-1300)/ 564 (176-3180)	1/ **0.77**	0.335 (0-4.46)/ 0.085 (0-4.10)	5/ **3.94**	9.86 (0-72.5)/ 57.3 (0.225-92.5)	4/ **0.17**	6.73 (6.73-6.73)/ 5.21 (5.21-5.21)	1/ 1.29
EER [b]	2.56(0.140-563)/ 4.49(0.450-224)	11/ **0.57**	381 (82.3-3490)/ 633 (54.5-39100)	10/ **0.60**	0.573 (0-10.5)/ 0.242 (0-14.0)	13/ **2.37**	4.92 (0-64.0)/ 38.7 (0.152-106)	9/ **0.13**	8.00(3.58-11.9)/ 6.95 (4.48-9.58)	9/ 1.15
Non-EER[c]	5.96(0.280-52.4)/ 9.08(0.780-168)	10/ **0.66**	792 (83.3-5080)/ 956 (128-21500)	8/ **0.83**	0.691 (0-2.95)/ 0.248 (3.45)	9/ **2.79**	9.14 (2.09-44.2)/ 33.0 (5.50-92.5)	8/ **0.28**	10.8 (6.48-13.8)/ 9.89 (7.19-20.6)	6/ 1.09
p-values:		<0.01		<0.01		<0.01		<0.01		0.34
Road Proximity										
<100 m	1.540 (0.198-15.8)/ 2.57 (0.194-29.2)	15/ **0.60**	642 (83.3-5080)/ 870 (54.5-39100)	12/ **0.74**	0.524 (0-4.46)/ 0.129 (0-4.10)	15/ **4.06**	4.94 (0-42.0)/ 38.0 (0-103)	13/ **0.13**	10.1 (6.53-13.8)/ 9.58 (5.21-20.6)	9/ **1.05**
100-200 m	0.685 (0.050-7.97)/ 1.71 (0.159-79.1)	5/ **0.40**	388 (82.3-4460)/ 614 (97.0-11000)	7/ **0.63**	0.621 (0-2.75)/ 0.251 (0-3.01)	7/ **2.47**	5.84 (1.78-59.5)/ 38.6 (0-106)	5/ **0.15**	6.48 (3.58-8.62)/ 6.55 (4.48-7.78)	7/ **0.99**
>200 m	1.09 (0.10-198)/ 1.27 (0.085-22.4)	6/ **0.85**	-	0/ -	0.222 (0-10.5)/ 0 (0-14.0)	5/ **-**	0 (0-72.5)/ 49.0 (0.225-95.8)	3/ **0.0**	-	0/ -
p-values:		<0.01				<0.01		<0.01		

Concentrations: Indoor Median (Indoor Range) / Outdoor Median (Outdoor Range)

	$PM_{2.5}$ [#/cm^3]	n/ **(I/O)**	BC [ng/m^3]	n/ **(I/O)**	CO [ppm]	n/ **(I/O)**	O_3 [ppb]	n/ **(I/O)**	NO_2 [ppb]*	n/ **(I/O)**
Wildfire Plume Density										
None	2.15(0.140-44.8)/ 3.36 (0.240-224)	7/ **0.64**	422 (82.3-3490)/ 590 (98.3-6900)	5/ **0.72**	0.526 (0-3.23)/ 0.224 (0-4.10)	9/ **2.35**	7.20 (0-72.5)/ 41.7 (0.152-92.5)	7/ **0.17**	6.39(3.58-10.1)/ 5.56 (4.48-9.24)	5/ 1.14
Low	3.25(0.280-52.4)/ 4.81(0.650-58.3)	7/ **0.68**	568 (144-4700)/ 745 (97.0-8280)	3/ **0.80**	0.605 (0-10.5) / 0.206 (0-14.0)	7/ **2.94**	4.93 (0-64.0)/ 46.6 (9.05-106)	4/ **0.11**	11.8 (8.00-13.8)/ 9.60 (6.55-11.1)	3/ 1.22
Medium	6.42(0.710-563)/ 7.49(0.750-168)	9/ **0.86**	632 (83.3-5080)/ 857 (54.5-39100)	8/ **0.74**	0.528 (0-5.30)/ 0.253 (0-1.90)	8/ **2.09**	8.05 (0-41.3)/ 33.7 (1.28-76.9)	7/ **0.24**	8.96 (6.48-11.9)/ 9.39 (7.19-10.2)	6/ 0.96
High	9.85(4.08-30.4)/ 24.9(8.44-165)	3/ **0.40**	495 (98.3-4320)/ 948 (176-21500)	3/ **0.52**	0.88(0.26-4.46)/ 0.278 (0-2.80)	3/ **3.17**	6.17 (2.68-11.3)/ 34.5 (5.50-80.5)	3/ **0.18**	10.1 (6.73-13.4)/ 12.9 (5.21-20.6)	2/ 0.78
p-values:		<0.01		<0.01		<0.01		<0.01		0.46
Mechanical Ventilation										
Present	2.95(0.560-44.8)/ 3.71(0.550-111)	4/ **0.80**	448 (98.3-2290)/ 622 (98.3-6290)	3/ **0.72**	0.442 (0-4.46)/ 0.180 (0-4.10)	5/ **2.46**	7.43 (0-59.5)/ 37.6 (0.152-92.5)	5/ **0.20**	6.73 (3.58-8.06)/ 5.56 (5.21-6.95)	3/ 1.21
Absent	3.43(0.140-563)/ 5.03(0.240-224)	22/ **0.68**	541 (82.3-5080)/ 787 (54.5-39100)	16/ **0.69**	0.602 (0-10.5)/ 0.237 (0-1.40)	22/ **2.54**	7.20 (0-72.5)/ 38.5 (0.225-106)	16/ **0.19**	9.30 (5.04-13.8)/ 9.24 (4.48-20.6)	13/ 1.01
p-values:		<0.01		<0.01		<0.01		<0.01		0.94
Hours Windows Open										
0	1.13(0.314-6.71)/ 2.44(0.194-54.0)	3/ **0.46**	219 (98.9-924)/ 784 (54.5-39100)	2/ **0.28**	0.385 (0-3.23)/ 0.0582(0-2.89)	3/ **6.61**	0 (0-20.5)/ 40.2 (0-85.7)	3/ **0**	5.05 (3.58-6.53)/ 7.39 (5.56-9.23)	2/ 0.68
1-6	0.544(0-4.31)/ 1.49(0.160-79.1)	4/ **0.36**	317 (82.2-2120)/ 540 (97-6950)	4/ **0.59**	0.692(0-2.75)/ 0.258(0-3.01)	4/ **2.68**	4.37 (1.78-9.83)/ 45.9 (0-106)	2/ **0.09**	7.19 (5.04-8.62)/ 6.01 (4.48-7.78)	4/ 1.20
7-12	0.932(0.10-15.8)/ 1.48(0.085-58.1)	5/ **0.63**	406 (109-3000)/ 800 (119-21500)	2/ **0.51**	0.301(0-10.4)/ 0 (0-14.0)	5/ -	0 (0-72.5)/ 49.4 (0-104)	4/ **0**	-	0
>12	1.50 (0.10-199)/ 1.78(0.120-59.2)	14/ **0.84**	739 (83.3-5100)/ 857 (58-17700)	11/ **0.86**	0.448(0-5.30)/ 0.175(0-3.45)	15/ **2.56**	8.82 (0-63.9)/ 35.2 (0-95.8)	12/ **0.25**	9.98 (6.48-13.8)/ 9.56 (5.21-9.23)	10/ 1.05
p-values:		<0.01		<0.01		<0.01		<0.01		0.11

Concentrations: Indoor Median (Indoor Range) /
Outdoor Median (Outdoor Range)

	$PM_{2.5}$ [#/cm^3]	n/ **(I/O†)**	BC [ng/m^3]	n/ **(I/O)**	CO [ppm]	n/ **(I/O)**	O_3 [ppb]	n/ **(I/O)**	NO_2 [ppb]*	n/ **(I/O)**
Gas Stoves										
Present	1.47 (0.100-18.5)/ 2.02 (0.275-59.2)	5/ **0.73**	597 (109-4400)/ 858 (119-21500)	3/ **0.70**	0.672 (0.08-2.95)/ 0.147 (0-1.13)	4/ **4.57**	6.00 (0-44.1)/ 36.1 (6.44-95.8)	4/ **0.17**	-	-
Absent	1.11 (0.050-199)/ 1.60 (0.085-79.1)	21/ **0.69**	503 (82.3-5080)/ 745 (54.5-39100)	16/ **0.67**	0.420 (0-10.4)/ 0.144 (0-14.0)	23/ **2.92**	4.43 (0-72.5)/ 40.6 (0-106)	17/ **0.11**	8.34 (3.58-13.8)/ 8.51 (4.48-20.6)	16/ -
p-values:		<0.01		<0.01		<0.01		<0.01		
Stove Hood Types										
Exhaust	0.978 (0.05-9.24)/ 2.39 (0.160-79.1)	8/ **0.41**	479 (98.3-4460)/ 829 (54.4-39100)	5/ **0.58**	0.473 (0-10.4)/ 0.159 (0-14.0)	8/ **2.97**	3.93 (0-42.0)/ 39.5 (0-85.7)	6/ **0.10**	6.63 (6.48-11.8)/ 8.21 (5.21-9.60)	4/ 0.81
Recirculating	1.04 (0.10-15.8)/ 1.24 (0.085-59.2)	12/ **0.81**	490 (82.3-5080)/ 693 (97.0-16200)	10/ **0.71**	0.389 (0-2.75)/ 0.050 (0-4.10)	12/ **7.78**	4.80 (0-72.5)/ 41.6 (0-106)	10/ **0.11**	8.34 (5.04-13.8)/ 7.37 (4.48-11.1)	8/ 1.13
Absent	1.62 (0.10-199)/ 1.76 (0.264-53.1)	6/ **0.92**	685 (99.0-4320)/ 908 (57.9-17700)	4/ **0.75**	0.592 (0-5.30)/ 0.258 (0-2.80)	7/ **2.29**	7.61 (0-44.1)/ 33.9 (0-95.8)	5/ **0.22**	10.9 (3.58-13.4)/ 9.88 (5.56-20.6)	4/ 1.10
p-values:		<0.01		<0.01		<0.01		<0.01		0.30

[*] NO_2 concentrations were TWA measurements, all other pollutants were time resolved (one-minute resolution)

[a] BG=Built Green; [b] EER=Energy Efficiency Retrofitted; [c] Non-EER=Non-Energy Efficiency Retrofitted (conventional homes as a control group)

I/O ratios that showed statistical significance (K-W test) in the mean differences ($p<0.05$) are shown in bold.

Supplement S4 B: Time Activity Diary

Home Weatherization
INDOOR AIR QUALITY & HEALTH

HOME ID:

Diary of Activities

This form will help to find out where indoor air pollution in your house comes from. Please see detailed instructions below

Start date: ____________________
Start time: ____________________
End date: ____________________
End time: ____________________

INSTRUCTIONS FOR USE:

At the end of each day, take a few minutes to record the time you spent doing each of the four listed activities and where you were when you did those activities. There is one page for each day of the study. The numbers in the box stand for hours of the day. For example, 5 in the morning is 5:00 a.m. to 5:59 a.m. Complete the box by circling each hour during which you spent any time doing any of the activities at any of the listed locations. It does not have to be for the entire hour.

Example:

If someone opened the kitchen windows from 6:30 am to 7:30 am, and the living room windows from 6:30 am to 8:30 am, you would complete the box like this.

DATE: 07/20/2016

DAY OF THE WEEK:
[✓ M] T W Th F Sa Sun

Activity: Windows and/or Doors Open

Day 1	Location	Morning	Afternoon	Evening	Early Morning (Night time)
	Kitchen	5 [✓ 6] [✓ 7] 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Living Room	5 [✓ 6] [✓ 7] [✓ 8] 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Bedroom	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Bathroom	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	When you are out of the house	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4

DATE: ___/___/___

DAY OF THE WEEK:

M T W Th F Sa Sun

Activity: Cooking

Day 1	Location	Morning	Afternoon	Evening	Early Morning (Night time)
	Kitchen – gas stove	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Kitchen – electric stove	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	When you are out of the house	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4

Activity: Windows and/or Doors Open

Day 1	Location	Morning	Afternoon	Evening	Early Morning (Night time)
	Kitchen	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Living Room	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Bedroom	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Bathroom	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	When you are out of the house	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4

Activity: Running Window Air Conditioner or Swamp Cooler

Day 1	Location	Morning	Afternoon	Evening	Early Morning (Night time)
	Kitchen	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Living Room	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Bedroom	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	When you are out of the house	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4

Activity: Running Kitchen and/or Bathroom Fan

Day 1	Location	Morning	Afternoon	Evening	Early Morning (Night time)
	Kitchen	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	Bathroom	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4
	When you are out of the house	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4

Chapter 5

Mechanical ventilation systems in low-income housing

5.1 Abstract

In the Colorado Home Energy Efficiency and Respiratory Health (CHEER) study, there were 11 homes with continuous exhaust mechanical ventilation (MV) system and eight more homes had heat recovery ventilation (HRV) systems installed. In Chapter 4, we found that MV systems significantly impact indoor pollutant concentrations during wildfire plume cover periods. This chapter investigates qualitatively as well as quantitatively the predicted indoor pollutant concentrations under different scenarios of having an indoor or outdoor short-term spike in pollutant concentrations. We first begin with a general introduction to the different types of MV systems. Then we investigate with numerical simulation the temporal variations of indoor concentrations of black carbon (BC) in a test home with comparisons to actual data from a home tested in Chapter 4. We finally investigate the use of air filtration incorporated with MV system which was identified as an effective way of ventilating homes in an energy-efficient way.

5.2 Introduction

An MV system generally refers to a fan that is dedicated to exhaust stale air from and supply outdoor air to the conditioned zone of a building for the sole purpose of maintaining acceptable indoor environmental quality, which includes maintaining thermal comfort, reducing any odors, and maintaining good indoor air quality (IAQ). Office buildings typically have a system that includes heating, ventilating and air-conditioning (HVAC) and often recirculate up to 80% of the indoor air, while bringing in 20% outside air for ventilation. Homes in the US are ventilated much differently, and the tradition has been to rely on infiltration or natural ventilation, as opposed to MV. Infiltration refers to air that passes through tiny cracks and openings in the building shell (envelope) structure (exterior walls, roof or windows) due to pressure and/or temperature differences. Natural ventilation refers to the exchange of air through open doors and windows in the home. As energy efficiency becomes more important in buildings due to climate change, a way to improve energy efficiency is to reduce infiltration and make the building shell tighter, but then this may result in much less air exchange. In low-rise residential buildings, mechanical ventilation is now required in many newly built homes (required in CA) or in weatherization programs that result in tight buildings. The American Society for Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) have published a standard (ASHRAE 62.2) that provides guidance for the minimum ventilation rates needed in homes with tight building shells.

MV systems for homes can vary greatly in design, operation, and features. MV systems can broadly be categorized into two types: (1) spot ventilation, and (2) whole house MV. Spot ventilation refers to the fans provided to bathrooms and kitchens with the main objective of exhausting polluted indoor air outside by placing the ventilation fan very close to the generation sites of the indoor air pollutants and high humidity. Spot ventilation systems are generally manually turned on with a wall-mounted switch.

Whole house MV, on the other hand, is intended to supply fresh air to the whole house. It can either be integrated with the main air-handler system in a home, or can be a stand-along unit totally independent from the main air-handling unit (AHU) and/or ductwork. The major types of whole house MV are listed below [157] along with the pictorial representation in Figure 5. 1.

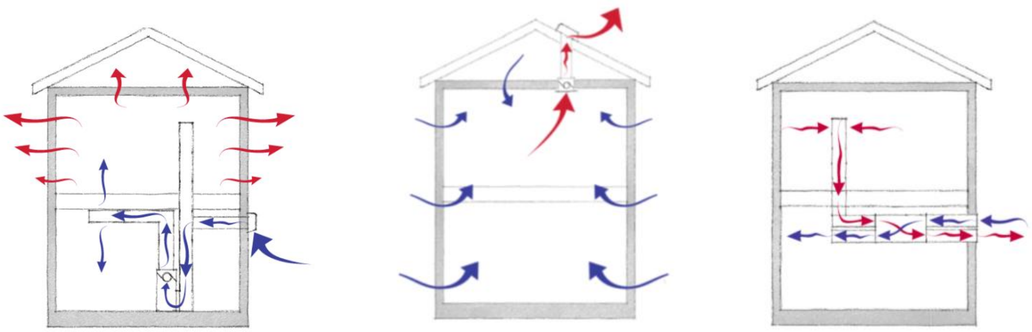


Figure 5. 1 Schematic diagrams showing airflow patterns in (a) supply-only (left), (b) exhaust-only (middle) and balanced (right) mechanical ventilation systems. Red arrows show the stale air exhausting from the building and blue arrows show the fresh outdoor air entering the building [158].

5.2.1 Supply ventilation system

This type of mechanical ventilation is recommended for hot or mixed climates. This type of system draws in fresh air from outside. It can be a stand-along unit or is integrated with the return air duct of the house forced air system with a dedicated outdoor air supply duct. The air is then conditioned and supplied to various zones. This type of system is “unbalanced” meaning the supply of air into the house creates a slight positive pressure in the interior. One potential drawback of this type of ventilation system is that the slight positive interior pressure can cause problems in homes located in colder climates, especially during winter season when hot and humid indoor air can get pushed by the positive pressure into the cracks and holes in the construction assembly and condense after encountering colder surfaces inside wall cavities thus causing moisture problems.

5.2.2 Exhaust ventilation system

This type of system exhausts air from the interior to the outdoors and relies on the leakage of the building envelope to bring in an equivalent amount of fresh air. This type of ventilation is suited for cold and dry climates and is not suitable for hot and humid climates since the hot and humid air in those climates can infiltrate indoors, cool, and condense after encountering colder surfaces of the construction assembly (Figure 5. 2).

Figure 5. 2 An exhaust type mechanical ventilation system installed in a bathroom ceiling

5.2.3 Balanced ventilation system

This type of MV system is suited for all types of climates. Balanced MV systems can comprise of two separate fans attached to the opposite sides of a building envelope, or it can also be a:

(1) Heat Recovery Ventilation (HRV) system, or an

(2) Energy Recovery Ventilation (ERV) system.

The HRV and ERV systems are very similar to each other. Both allow for heat and/or enthalpy exchange between the incoming fresh air from the outdoors and exhaust stale air from the indoors. The HRVs and ERVs are usually balanced, meaning they do not pressurize or depressurize the indoor air relative to outdoors.

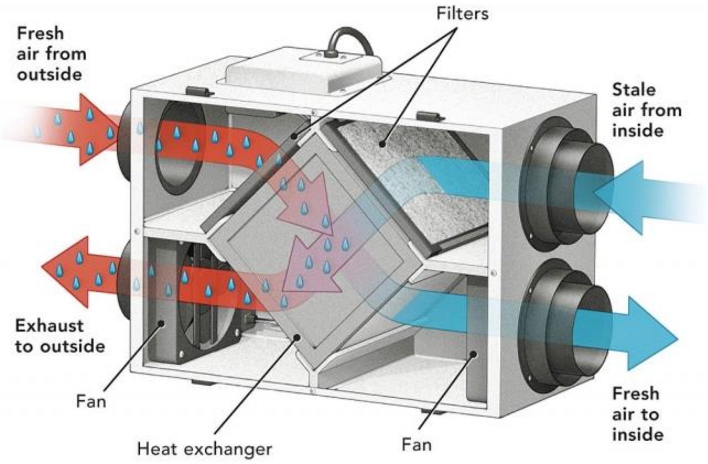


Figure 5. 3 Components of an ERV system [157]. HRV systems are almost identical in construction, the only difference being the material used in the core heat exchanger.

In HRVs, the incoming and exhausting air streams are passed through a highly conductive heat exchanger (usually made from aluminum) that does not allow the mixing of the two air streams, but only allows heat exchange between the two.

ERVs are almost exactly like HRV in terms of construction (Figure 5. 3), the only major difference being the heat exchanger "core" material which is made from corrugated paper, plastic or polymer material that are semi-permeable to moisture. The incoming fresh air stream still does not mix with the exhausting air stream, but the core heat exchanger allows the exchange of moisture (and thus the latent heat) between the two air streams.

5.3 Effect of continuous exhaust MV systems on annual average air exchange rates

Building airtightness in newly constructed homes are usually compared using the metric of air changes per hour at 50 Pascals (ACH50) measured with a blower door test. Besides ACH50, the output of a blower door test also includes information on the building leakage curve which is used to predict the annual average air exchange rate (AAER), often represented simply as air changes per hour (ACH) and reports the summer and winter ACH values separately accounting for the seasonal variability in the patterns of natural ventilation following the changes in stack and wind effects. The schematic diagram below (Figure 5. 4) shows the process of how ACH is estimated using an infiltration model developed by the Lawrence Berkeley National Lab (LBNL) [159].

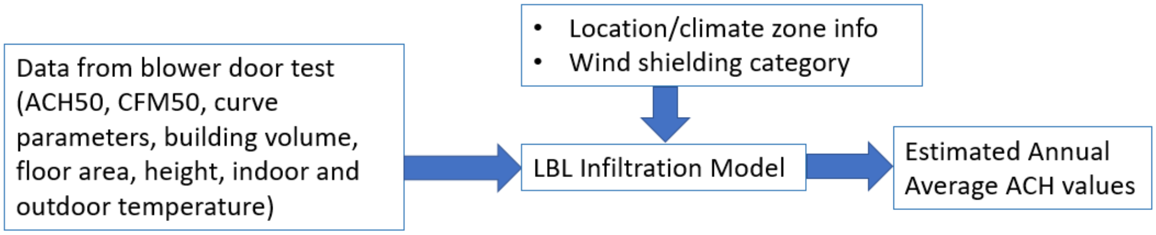


Figure 5. 4 Schematic representation of the ACH estimation procedure.

When conducting a blower door test in a home with continuously running exhaust MV that cannot be turned off, the negative indoor pressure caused by the blower door depressurization test will cause the damper located in the fan exhaust vent hood located on the building exterior (usually the roof) to close. The blower door test, therefore, will not see any (or insignificant) opening in the building shell, which will misrepresent the effect of the MV system. Since the MV system does actually induce more airflow in the building, hence, the ACH reported by the blower door test will be lower than what one can expect to see from a tracer gas decay method. To account for this discrepancy, one technique is to calculate the whole building ventilation rate based on the ASHRAE 62.2 Standard. If the fan flow rating is known, the estimation of ACH will be more accurate, but even if the actual fan flow rate is not known, ASHRAE 62.2 calculations will give a good estimate of the annual average ACH.

For the CHEER study homes with continuous exhaust MV systems, ASHRAE 62.2-2010 Standard was used. A newer version of the standard, ASHRAE 62.2-2013 is available for ventilation calculations in newly constructed residential homes; but knowing that the weatherization work done in the housing stock that we studied for the CHEER study took place before the year 2012, the older version (2010) of the ASHRAE standard was used.

Equation 5.1 is used to adjust the LBNL model reported ACH values to account for continuous MV homes. This method was developed by Palmiter and Bond (1991) [80].

$$AAER = \frac{(CFM + 0.5 \times CFM_{Mechanical})}{V} \times 60 \tag{5.1}$$

AAER is the annual average air exchange rate [1/hr]; CFM is the ventilation rate estimated with blower door test [cubic feet per minute]; $CFM_{Mechanical}$ is the airflow rate through the continuous mechanical ventilation fan; and V is the building volume [cubic feet]. Our main goal is to find $CFM_{Mechanical}$. If a direct measurement of this flow rate can be made using a balometer apparatus, the estimation of AAER will be more accurate. However, if this measurement is not possible due to various reasons, it can be assumed to have been properly sized as per the ASHRAE 62.2 standard and can be estimated with the following steps:

Step 1: Calculate the “base” rate:

$$Q = 0.01\, A_{floor} + 7.5\, (N_{br} + 1) \tag{5.2}$$

Where,

Q = base rate, [cfm]

A_{floor} = floor area, [ft^2]

N_{br} = number of bedrooms, not to be less than 1

Step 2: Calculate the "Supplemental Rate":

The supplemental rate considers already existing bathroom or kitchen exhaust fans (manually operable, intermittent) and operable windows. existing bathroom or kitchen exhaust fans need to be assessed to see whether they meet the required ventilation rates as per ASHRAE 62.2-2010 (the kitchen needs 100 cfm and each bathroom needs 50 cfm exhaust fan capacity). If the existing fan rated capacity is less than in the step above, it counts as a "ventilation deficit". The sum of all ventilation deficits is expressed in cfm. If the ventilation deficit is zero or negative (i.e. bathroom or kitchen manual exhaust rated fan capacity is more than 100 cfm or 50 cfm for kitchen and bathroom respectively), the ventilation deficit is taken as zero. If there is any number of operable windows in the kitchen or bathroom, 20 cfm can be discounted in each bathroom or kitchen from the ventilation deficit. Finally, if the existing fan rated capacity is not known or cannot be measured, treat it as zero (ASHRAE 62.2-2010, Section A3.1) (all existing kitchen and bathroom exhaust fans were treated as zero for our use). Equation xx below describes how to estimate the supplemental rate:

$$\begin{gathered}0.25\times \text{ Net ventilation deficit}\\ (\text{i.e. total deficit minus}\\ \text{discount from the presence of operable windows})\\ = \text{ Supplemental rate}\end{gathered} \tag{5.3}$$

Step 3: Calculate the "Infiltration Credit":

The infiltration credit can be included if a blower door test has been performed, and can be calculated as:

$$\text{Infiltration credit} = 0.5 \times (\text{CFM from blower door test} - \text{Default rate}) \tag{5.4}$$

Where,

$$Default\,rate = A_{floor} \times \frac{2\,cfm}{100ft^2} \tag{5.5}$$

Step 4: Calculate the "whole building rate" (CFM $_{\text{Mechanical}}$):

$$CFM_{Mechanical} = Base\,rate + Supplemental\,rate - Infiltration\,credit \tag{5.6}$$

Finally, putting the value of CFM $_{\text{Mechanical}}$ from Eq. (5.6) in Eq. (5.1) will give AAER.

The AAER and ACH50 were linearly related as expected, considering data from all the homes enrolled in the CHEER study (refer to Chapter 3, Figure 3.2).

5.4 MV systems and indoor air quality

Determining what type of MV system to install requires complex analysis and a misjudgment in this part can lead to indoor environmental quality (IEQ) problems in the long-run through one or more of the following ways:

- Introducing additional temperature and moisture to the indoor environment creating thermal discomfort and additional energy demand for air conditioning
- Positive pressure indoors can cause mold problems in colder climates. Indoor humid air is pushed in through cracks and openings into the building shell structure and there it can condense after contacting colder surfaces. Over a long time, mold can grow in the moist and damp areas inside the wall cavities.
- If the indoor air is constantly negative in pressure with respect to outdoors as in exhaust MV, outdoor pollutants can find their way easily into the indoor environment. Negative indoor pressure also poses a danger of the exhaust flue gases from combustion devices like the AHU (furnace) and hot water tank being back-drafted into the living spaces.
- Even in balanced HRV/ERV systems, excessive moisture in the exhausting or incoming air streams can condense into the interior of the system. If left unclean for a long time, the dampness inside can cause mold or bacteria growth, thereby affecting occupant health.

In terms of air filtration, exhaust type MV systems do not have any provision for air filtration. Supply-only MV systems have the option of relatively more convenient air filter integration before the intake fan. HRV/ERV systems are generally provided with air filters attached to the heat exchanger core, but with the primary objective of protecting the core from large debris, not filter the indoor air. The primary AHU air filter is assigned the task of cleaning indoor air. However, if the AHU air filter is of a low MERV[1] rating or equivalent, or the filter is left unchanged or uncleaned for a very long period of time, it cannot help much in removing dust from the indoor air, and can in fact act as an additional source of indoor dust resuspension back into the AHU airstream[160]. AHU air filters are also mostly designed only to remove particulate matter, and cannot scrub gas phase pollutants like carbon dioxide, carbon monoxide, and nitrogen dioxide from indoor air which have significant negative effects on human health.

5.5 Case study: Homes from the CHEER study

A subset of the homes enrolled in the CHEER study comprised of 11 homes enrolled through collaboration with Boulder Housing Partners (BHP). The BHP homes were very different in terms of construction than the rest of the homes enrolled in the CHEER study. BHP homes had split air-conditioning systems for cooling, HRV (in eight out of 11) and electric baseboards for heating, and all BHP homes had electric water heaters, electric stoves and electric washers and dryers.

Table 5. 1 summarizes the blower door test results for the BHP Homes which were “built green” (BG), meaning that the home was built with energy efficiency measures implemented. All the BHP homes were built in the year 2010.

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[1] MERV = Minimum Efficiency Rating Value

Table 5. 1 ACH50 Results for “built green” homes (N=11)

Home ID	Single family home*	ACH50 (hr^{-1})	Notes
172	N	6.36	HRV installed
174	N	2.83	HRV installed
178	N	6.72	HRV installed
180	N	8.87	HRV installed
186	N	11.32	HRV installed
189	Y	8.38	No MV†
190	N	5.89	HRV installed
192	Y	9.6	No MV
193	Y	9.18	No MV
213	Y	3.96	HRV installed
214	Y	3.75	HRV installed

*Y=Yes, N=No (duplex/townhouse); †MV = Mechanical Ventilation

Figure 5. 5 shows the distribution of blower door test results for the built green study homes. For comparison, also shown in the figures is the distribution of blower door results for the other homes that were also enrolled in the CHEER study, but that were not built green and did not have added ventilation. The 11 built green homes from BHP had lower mean and median values as well as lower spread of ACH50 values when compared to the other 215 homes (non-BHP homes) in our data sets, which were not built green.

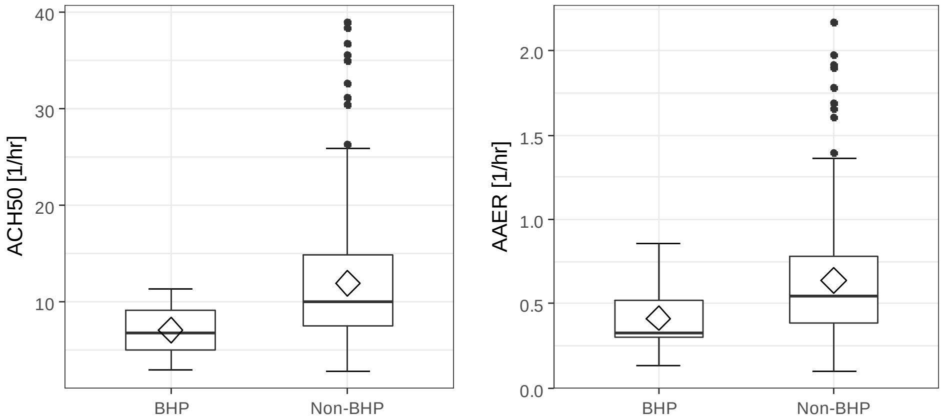

Figure 5. 5 Summary of ACH50 (left) and AAER (right) distributions comparing BHP homes (n=11 homes) to other study homes (n=215). The center diamond represents sample arithmetic mean in each box and whisker diagram (t-test: $p<0.05$ for both ACH50 and AAER).

The HRV systems installed in the BHP homes were locked in a mechanical room (only accessible through the facilities management) controlled through a timer switch and the lengths of operation scheduled varied from home to home (Figure 5. 6). All the HRV systems we investigated in the eight BHP homes were in good condition and clean from the inside with very little dust loading on the core filters. The return grills for the HRV systems were in bathrooms and the supply diffusers were located in bedrooms and living rooms. The intake and exhaust vents of the HRV systems were located on the side of the buildings, usually at the ceiling level of the second floor.

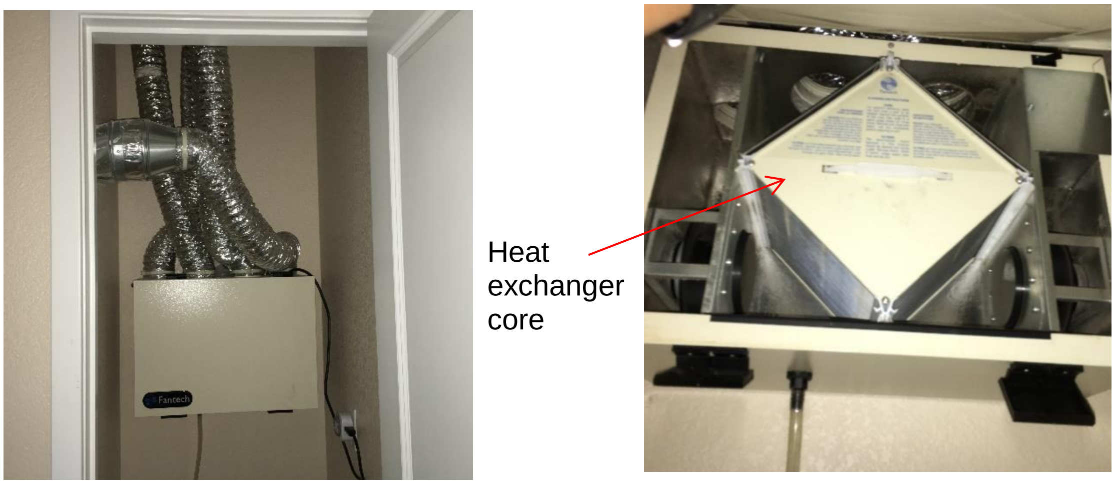

Figure 5. 6 HRV system in one of the BHP homes with the casing closed (left), and with the casing open (right).

5.5.1 Adequacy of ventilation

Depending upon the floor area, number of bedrooms, number of kitchens and bathrooms, and rooms with operable windows in the house, the ASHRAE 62.2-2010 standard was used to calculate the required whole building ventilation rates ($\text{CFM}_{\text{Mechanical}}$) in the BHP homes with MV systems (Table 5. 2Table 5. 2 Calculated whole building mechanical ventilation flow rates for the BHP homes based on ASHRAE 62.2 Standard). The maximum fan capacity of the HRV systems installed was reported as 104 cubic feet of air per minute (cfm)[161]. The number of hours of operation were estimated for the HRV systems to provide the required whole building ventilation rates for 24 hours. (We did not record the number of hours each HRV unit was operating, and this should be done as a safety-check in the BHP homes to ensure that the occupants are getting enough ventilation air as per the ASHRAE 62.2 Standard.)

Table 5. 2 Calculated whole building mechanical ventilation flow rates for the BHP homes based on ASHRAE 62.2 Standard

Home ID	A_{floor}[a] [ft^2]	No. of bedrooms	Required Whole Building Rate (cfm)[b]	Hours of HRV operation required to meet the required whole building rate for 24 hours
172	782	2	60.9	14
174	768	3	70.6	16
178	768	2	59.8	14
180	703	2	57.7	13
186	730	2	37.5	9
190	786	2	48.2	11
213	949	3	77.2	18
214	851	2	56.1	13

[a] Floor area
[b] cubic feet per minute of the required mechanical ventilation fan capacity

By contrast, the whole building ventilation rates of other homes (non-BHP) in the CHEER study which had exhaust-only MVs were relatively higher, as shown in Table 5. 3 below.

Table 5. 3 Building ventilation details of other homes (non-BHP) in the CHEER study with continuous MV installed.

Home ID	Year Built	ACH50 [hr^{-1}]	A_{floor}[a] [ft^2]	No. of bedrooms	Calculated Whole Building Rate (cfm)[b]
140	2002	8.79	1514	2	54.8
141	1962	6.33	1332	4	80.0
179	1980	9.58	1385	3	47.9
185	2004	3.67	2811	3	85.0
194	1960	4.06	1537	3	75.7
224	1997	4.78	3282	4	102.8
229	1958	5.01	1864	3	78.1
295	1982	6.43	1770	3	78.9
299	1980	9.23	1906	3	68.1
423	1960	5.7	1521	4	82.1
427	1956	9.21	2094	5	73.5

[a] Floor area
[b] cubic feet per minute of the required mechanical ventilation fan capacity

5.5.2 Observations from BHP homes

Some major qualitative observations made from the BHP homes regarding indoor air quality are as follows:

- Most homes were within desired bounds for building air-tightness (IECC 2012).
- The ACH50 in two homes were too low (IECC 2012), and HRV was the only method of ventilation available besides natural infiltration through leakage in building envelope.
- During our home visits, a few occupants complained about the general thermal comfort of BHP homes, especially during winter time.
- In some homes, the occupants had sealed the HRV supply diffuser by taping plastic sheet on the diffuser because they experienced cold air being blown on them during winter time.
- Awareness/education for the occupants regarding adequate ventilation in these homes seems to be a necessity since the HRV supply is their primary mode of ventilation.
- Since there are no additional AHUs in the BHP homes with indoor air cleaning filters, the homes with only HRV as the primary ventilation mode either need a high efficiency filter coupled with the HRV before the ventilation air is supplied to the indoor spaces, or there needs to be additional stand-alone air filters in the homes. In the absence of both, outdoor pollutants can be expected to build up indoors during the times when outdoor air has elevated levels of pollutants.

5.6 Modeling the effects of MV on indoor concentrations of black carbon

5.6.1 Introduction

In order to study the effects of different types and characteristics of MV systems on indoor air contaminant concentrations, a modeling study was performed in which indoor concentrations of airborne black carbon (BC) particles were simulated under different conditions using the software CONTAM, which is a multi-zone network indoor air quality and ventilation analysis software developed and maintained by the National Institute of Standards and Technology[162].

For the part of the CHEER study in which we studied the infiltration of outdoor air pollutants related to wildfire and traffic (chapter 4), we collected indoor and outdoor measurements of various pollutants. Two of those homes also had exhaust MV systems and three of them had HRV systems. Unfortunately, the particulate matter (PM) measurement in one of the homes with an exhaust MV system was corrupted, and indoor-outdoor comparisons could not be made. However, the data on black carbon (BC) measured with microAeth® AE51 aethalometers (AE51; AethLabs, San Francisco, CA, USA) were still available. Hence, hourly averaged BC data are used for indoor-outdoor comparison of pollutants. Black carbon come from traffic exhaust and has been measured in homes that are located close to a major road[163]. Another major source is wildfire smoke. The test home chosen for this part of the study was the only home with a continuous exhaust MV type with all the windows closed during indoor sampling. The study home location was not being affected by wildfire plumes during the time of sampling.

5.6.2 Methods

The CONTAM modeling software was used to simulate the transient behavior of one test home (Home ID T194) fitted with an exhaust-only MV system. This home was chosen because it was confirmed from the time-activity diary filled out by the participant that all the windows in the house were closed throughout the entire two-day sampling period, and we also had minute-resolution black carbon (BC) concentration data for this house (both indoors and outdoors).

5.6.2.1 Description of CONTAM methods and governing equations[164]

CONTAM simulations are based on the conservation of mass in a well-mixed control volume (c.v.). Air is treated as an ideal gas in CONTAM, which follows the ideal gas law:

$$\rho = m/V = P/(RT) \tag{5.7}$$

where

$m =$ the mass of air

$V =$ a given volume

$P =$ the absolute pressure

$R =$ the gas constant for air, and

$T =$ the absolute temperature.

The mass of air inside the c.v. is the sum of masses of the individual contaminants, α

$$m_i = \sum_{\alpha} \mathrm{m}_{\mathrm{i}}^{\alpha} \tag{5.8}$$

The volumetric concentration of contaminant α in c.v. i is defined as

$$C_i^\alpha = m_i^\alpha \, / \, m_i \tag{5.9}$$

Since air is a mixture of different species, the value of the gas constant for air in a c.v. is given by

$$R_i = \sum\nolimits_\alpha R^\alpha C_i^\alpha \tag{5.10}$$

where R_i = the gas constant of species α which equals the universal gas constant, 8314 J/(kmol·K), divided by the molar mass of α (kg/kmol). Under typical conditions only water vapor has an impact on the properties of air and even that can be ignored as an initial approximation. There is a standard definition of species concentrations for dry air that yields an effective molar mass of 28.96 kg/kmol and a gas constant of 287.1 J/(kg·K). The density of air is taken as 1.204 kg/m^3 as computed by equation (5.7).

With CONTAM a contaminant may be added to a c.v. i by:

- inward airflows through one or more flow paths at the rate $\sum_j F_{j\rightarrow i}\left(1-\eta_j^\alpha\right)C_j^\alpha$, where $F_{j\rightarrow i}$ is the rate of air mass flow from c.v. j to c.v. i and η_j^α is the filter efficiency in the path.
- species generation at the rate G_i^α.

A species may be removed from the c.v. by:

- outward airflows from the zone at a rate of $\sum_j F_{i\rightarrow j} C_i^\alpha$, where $F_{i\rightarrow j}$ is the rate of air mass flow from c.v. i to c.v. j, and
- species removal at the rate $R_i^\alpha C_i^\alpha$ where R_i^α is a removal coefficient.

A species may be added or removed by first-order chemical reactions with other species at the rate $\sum_{\beta} K^{\alpha,\beta} m_i^{\beta}$, where $K^{\alpha,\beta}$ is the kinetic reaction coefficient in the c.v. i between species α and β. (Sign convention: positive K for generation and negative K for removal).

Combining these processes into a single equation for the rate of mass gain of a species α in a c.v. i gives:

$$\frac{dm_i^{\alpha}}{dt} = \sum\nolimits_j F_{j\to i}\,(1-\eta_j^{\alpha})C_j^{\alpha} + G_i^{\alpha} + m_i \sum\nolimits_{\beta} K^{\alpha,\beta}\,C_i^{\beta} - \sum\nolimits_j F_{i\to j}\,C_i^{\alpha} - R_i^{\alpha} C_i^{\alpha} \tag{5.11}$$

The transient conservation of species mass in a control volume is given by:

(mass of contaminant α in c.v. i at time $t + \Delta t$) =

(mass of contaminant α in c.v. i at time t) +

$\Delta t \times$ (rate gain of contaminant α – rate loss of contaminant α)

Or in numerical form as:

$$\rho_i V_i C_i^{\alpha}|_{t+\Delta t} \;\approx\; \rho_i V_i C_i^{\alpha}|_t + \\ \Delta t \cdot \left[\sum\nolimits_j F_{j\to i}\,(1-\eta_j^{\alpha})C_j^{\alpha} + G_i^{\alpha} + m_i \sum\nolimits_{\beta} K^{\alpha,\beta}\,C_i^{\beta} - \sum\nolimits_j F_{i\to j}\,C_i^{\alpha} - R_i^{\alpha} C_i^{\alpha}\right]_{t+\delta t} \tag{5.12}$$

For the numerical calculation of contaminant concentrations, several possible solutions for equation (11) can be characterized by the choice of δt to determine the rate of gain or loss. CONTAM has traditionally chosen $\delta t = \Delta t$. Equation (5.12) then becomes:

$$\left[\rho_i V_i + \Delta t \cdot \left(\sum\nolimits_j F_{i\to j} + R_i^\alpha\right)\right] C_i^\alpha|_{t+\Delta t}$$
$$\approx \rho_i V_i C_i^\alpha|_t + \Delta t \cdot \left[\sum\nolimits_j F_{j\to i}\left(1-\eta_j^\alpha\right)C_j^\alpha + G_i^\alpha + m_i \sum\nolimits_\beta K^{\alpha,\beta} C_i^\beta\right]_{t+\Delta t} \tag{5.13}$$

All concentrations C_i^α at time $t + \Delta t$ are functions of various other concentrations also at $t + \Delta t$. This is the *standard implicit method*, and it requires that a full set of equations (5.13) must be solved simultaneously.

The number of equations, N, equals the number of species times the number of control volumes. In a traditional Gauss elimination (or LU decomposition) solution the computation time is proportional to N^3, making it impractical for large problems. CONTAM offers three solution methods which take advantage of matrix sparsity to handle cases with large numbers of equations. These are a *direct skyline algorithm*, an iterative biconjugate gradient (BCG) algorithm, and an *iterative successive over relaxation* (SOR) algorithm (LU decomposition is provided only for testing and benchmarking.) The skyline algorithm is very fast for problems of intermediate size but can be slow for large problems. The SOR algorithm requires much less memory and may be faster for large problems unless there are convergence difficulties. In such cases an option is to try the BCG solution, although it may also experience convergence difficulties. It can be useful to test the different methods to determine which will give optimum performance before doing a long transient simulation.

A more accurate solution can be obtained by choosing $\Delta t = \Delta t/2$ which means average conditions during the time step. This has been implemented in CONTAM by a trapezoidal integration which still requires solving the full set of simultaneous equations.

We can also choose $\Delta t = 0$. In this case equation (5.12) becomes:

$$\rho_i V_i C_i^{\alpha}|_{t+\Delta t} \approx \rho_i V_i C_i^{\alpha}|_t + \Delta t \cdot \left[\sum_j F_{j\to i} \left(1-\eta_j^{\alpha}\right) C_j^{\alpha} + G_i^{\alpha} + m_i \sum_{\beta} K^{\alpha,\beta}\, C_i^{\beta} - \sum_j F_{i\to j}\, C_i^{\alpha} - R_i^{\alpha} C_i^{\alpha} \right]_t \tag{5.14}$$

The reader is guided to CONTAM user guide[164] for further details on numerical calculations and issues related to the solution stability.

5.6.2.2 Description of the single-zone house model

The test house was modelled as one continuous conditioned well-mixed zone (one box) with the indoors and outdoors separated by a rectangular wall representing the building envelope (Figure 5. 7). Three air exchange routes were defined on the building envelope rectangle: a leakage area (information available from blower door test), continuous mechanical ventilation (information available from the ASHRAE 62.2 calculations), and a window of size 4ft X 3ft (hypothetical case created to investigate the effect of window opening). Although CONTAM can do much more detailed analysis taking into consideration the different air-conditioning zones (representing different rooms, hallways and ductwork), data on zonal pressure differences and air exchange rates between different rooms within the same house were not available, the simplified single-zone model was used to simulate the conditions of different modes of MV system operations.

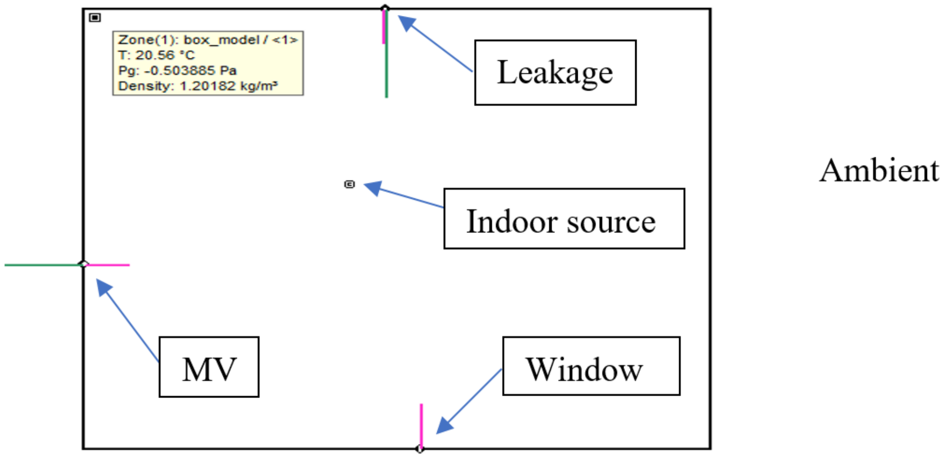

Figure 5. 7 CONTAM box model representation of the house as a single conditioned well-mixed zone. The green bars show the direction of airflow and the red bars show the normal direction of the pressure gradient.

5.6.2.3 Simulation parameters

<u>Home T194 characteristics:</u>

Floor Area= 1537 sq. ft.

Volume = 12038 cu. ft.

ACH50=4.06 hr^{-1}

AAER=0.39 hr^{-1} (considering continuous exhaust MV)

Effective leakage area = 45.2 in^2 (±4.7%) @ 4 Pa

Leakage curve coefficient, C = 65.1 (±7.6%)

Leakage curve exponent, n= 0.646 (±0.021)

Note: Measurement uncertainties are as reported by the blower door test software.

Species parameters (BC, assuming diesel exhaust emissions as source)

Molecular weight = 12 kg/kmol (Carbon)

Diffusion Coefficient = 2E-005 m^2/s (same as dry air, CONTAM default)

Mean diameter = 2.5 µm (hypothetical case)

Effective density = 1.1 g/cm^3 [165]

Specific heat = 0.71 kJ/(kgK) (carbon/graphite) [166]

5.6.2.4 Scenarios simulated

- Continuous exhaust MV system running with all windows closed + indoor source
- Continuous exhaust MV system running with all windows closed + No indoor source
- MV system failure + windows closed
- MV system running, windows closed and there is a sudden spike in outdoor BC concentration
- MV system running, windows open, with sudden spike in outdoor BC concentration
- Continuous MV versus balanced HRV (with filtration)

The generation rate of indoor source was created to match the peak concentration as seen from real measurement by iteratively controlling the source strength. In addition, the ambient temperature was scheduled to cycle between 68 to 85 ºF, as per the real measurements taken in home T194.

5.6.3 Results and Discussion

Figure 5. 8 shows the time series of BC concentration measurements taken at home T194 on Jul 25-27, 2017. The large indoor peak on Jul 25 was verified as a cooking related event.

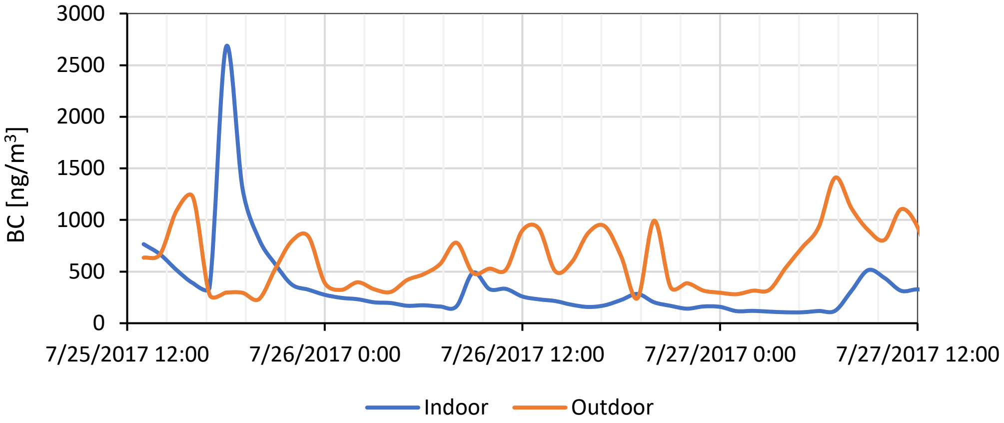

Figure 5. 8 Indoor and outdoor BC concentration measurements.

Next, a simulation was done with a 4ft X 3ft window left open without the MV system running (Figure 5. 9). The indoor concentration follows the ambient concentration profile closely.

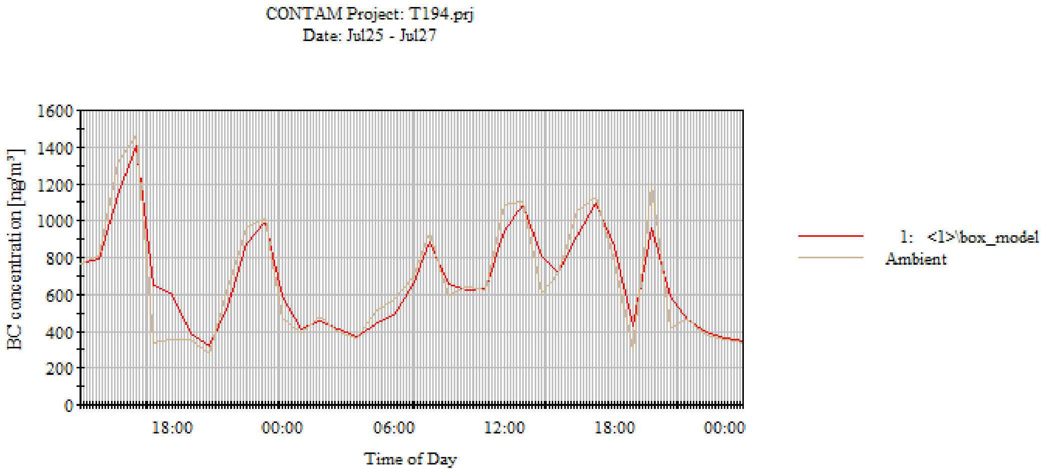

Figure 5. 9 All windows open, no MV

Next, a simulation was done for BC infiltration indoors without any indoor source, with all exterior windows closed, and the continuous exhaust MV system running (Figure 5. 10). The response of the indoor concentration following the outdoor concentration profile is dampened due to the lower air exchange compared to the condition of windows left open.

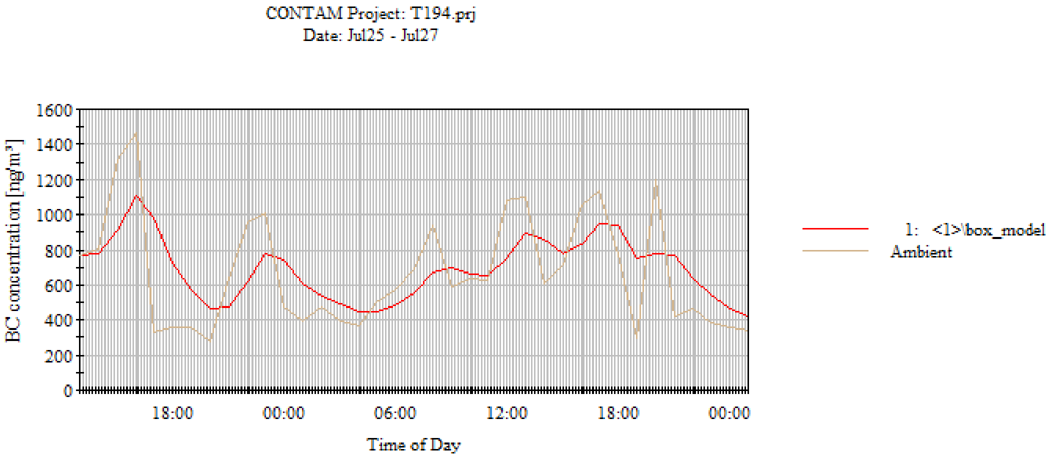

Figure 5. 10 Simulation of outdoor BC infiltration without any indoor source, windows closed, only MV running

In another test case (Figure 5. 11), an indoor source was introduced to match the indoor source related spike as seen in Figure 5. 8. Although the peak concentration was matched, the simulated indoor concentrations after July 26 midnight was higher than the actual measurements (about two times as high). There can be many reasons for this: the decay rates due to deposition might have affected the results, the MV system flow rate could have been different, local effects might have affected the measurements, and the concentrations might not have been well mixed.

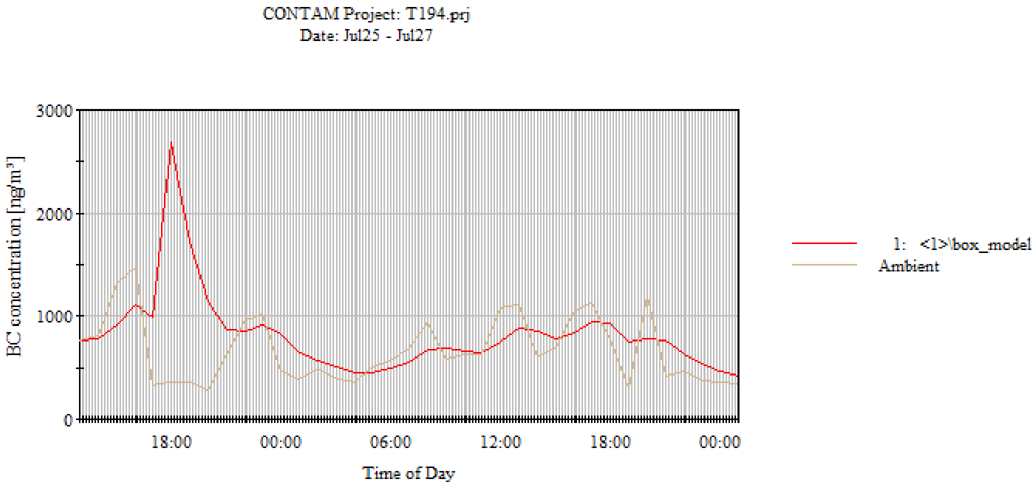

Figure 5. 11 Simulation with measured outdoor BC data, MV running at 100 cfm and an indoor source emulated, all windows closed

In another test case (Figure 5. 12), indoor BC concentrations were simulated to investigate the effect of exhaust MV failure with all the windows closed with the indoor source introduced as in Figure 5. 11. The indoor concentrations remain elevated at a high concentration above 3500 ng/m^3 for the rest of the simulation.

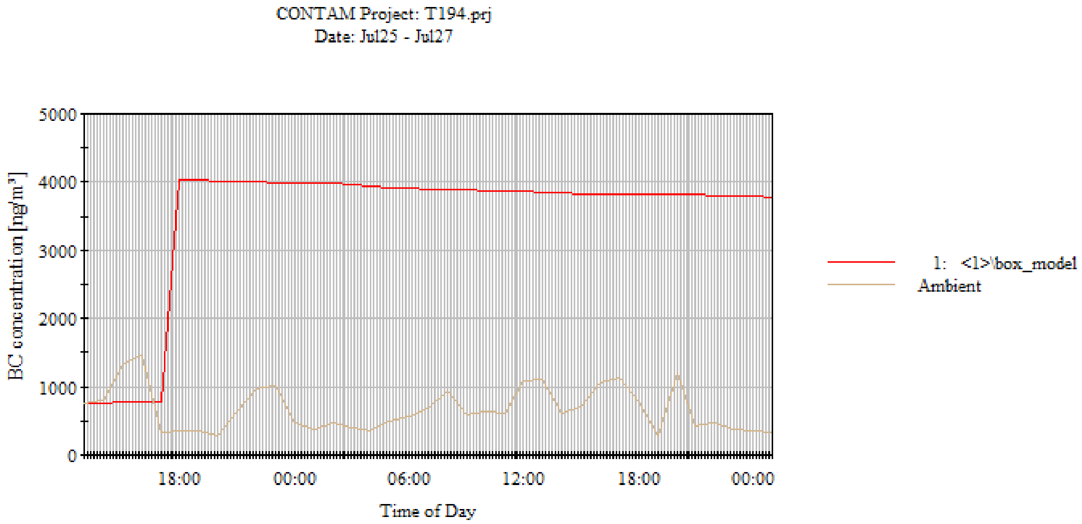

Figure 5. 12 Simulation of MV system failure scenario

Figure 5. 13 shows a simulation without an indoor source, the exterior windows closed, only exhaust MV providing the ventilation, and an outdoor spike in BC concentrations due to an outdoor event (like a diesel truck producing BC emissions close by). The indoor concentration spike in this case is roughly half of the outdoor concentration spike's peak value. It takes about six hours for the indoor elevation of BC to fall back down to normal levels.

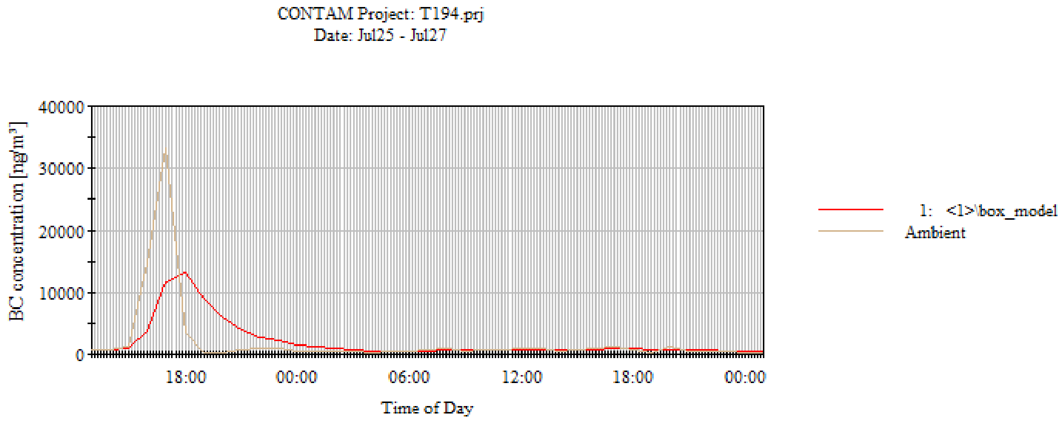

Figure 5. 13 Absence of indoor source, presence of outdoor source

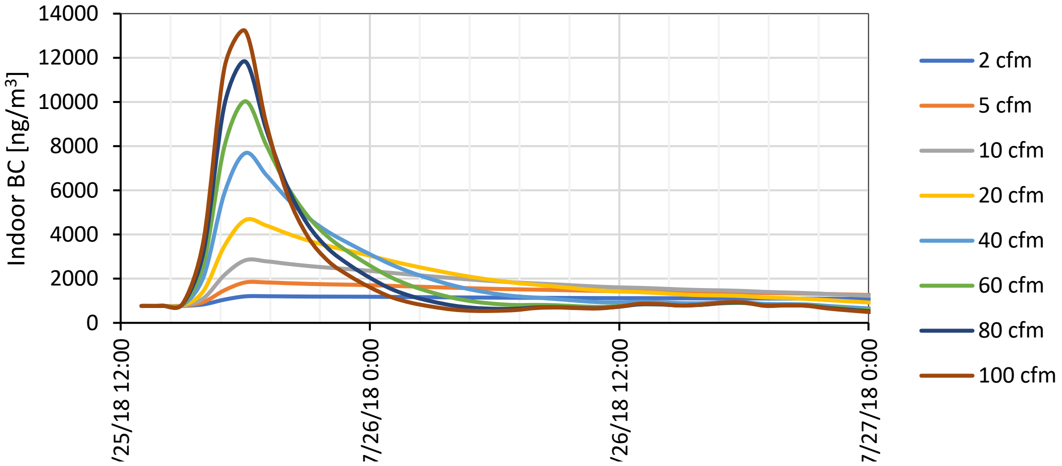

Figure 5. 14 Response of indoor BC concentrations to an outdoor spike for varying MV flow rates

Keeping the same ambient conditions as in Figure 5. 13, the exhaust MV flow rates were varied. As depicted in Figure 5. 14, the lower the MV flow rates, the lower will be the peak indoor BC concentration. However, the higher the MV flow rate, even though the peak indoor concentration is maximized, the relaxation time for the concentration to fall back to normal levels is also shorter, provided that the outdoor spike only happened for a short duration.

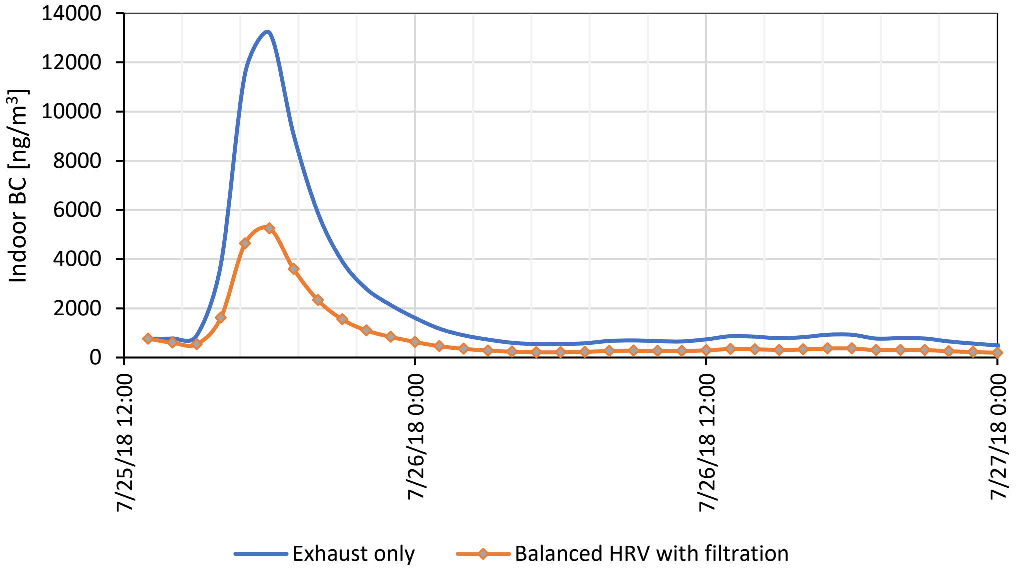

Figure 5. 15 HRV with filtration at 100 cfm

In the final simulation test case (Figure 5. 15), the exhaust MV was replaced by a continuous HRV with a 8.5” (216mm) X 12.5” (318mm) X 0.125 (3mm), EU3 rating filter [161] at the HRV core. Results show that a high cfm exhaust-only MV system can cause an indoor BC spike of up to 13,000 ng/m^3, while an HRV system with single-pass filtration (even with a relatively low efficiency filter) will result in a maximum indoor concentration spike of up to 5000 ng/m^3. This peak concentration spike can be expected to be lowered if the HRV is coupled with the return air duct in a conventional residential air handler that is clean and is fitted with a high efficiency filter.

5.7 Conclusions

Mechanical ventilation systems are installed in homes primarily to improve the indoor environmental quality and are especially recommended in tight homes. However, MV can cause indoor air quality problems if not installed properly, and if the home is located in an area with elevated outdoor air pollution. Although exhaust MV systems can help in quickly removing indoor spikes in pollutant concentrations caused by indoor sources like cooking, the peak exposure can be reduced by using HRV systems instead of exhaust-only ventilation because HRV systems can offer the opportunity to use a filtration technology at the supply end. Also, indoor concentrations spikes can be caused due to various factors happening both indoors and outdoors, and the best way to economize the use of HRV and get the maximum benefit in terms of indoor air quality is to incorporate active sensing technology in HRV systems that monitors both indoor and outdoor pollutants simultaneously. It is a matter of economic optimization in engineering design of the systems, but the emerging low-cost sensing technologies have a lot to offer in this regard.

Chapter 7

Summary and Concluding Remarks

The work presented here reviewed a compilation of studies that have contributed to increase our knowledge of how building characteristics, outdoor air pollution, and occupant behavior collectively affect the occupants' exposure to harmful air contaminants in the indoor environments of low-income homes.

At first, we took a detailed look at the air-sealing energy retrofits done to the building envelopes in low-income homes in relation to indoor air quality indicators (Chapter 3). We found that window weather-stripping and HVAC ductwork sealing contribute relatively more to increasing the building air-tightness than other activities like door weather-stripping, door and window frame caulking and foam-sealing of minor cracks and openings on the lateral walls. However, the influence on annual average air exchange rates of the buildings due to air-sealing retrofits were insignificant compared to the building characteristics like building volume and age. The best way to make a house more airtight is to build it tight in the first place. It was also seen that leakier homes tend to have higher degree of indoor dust and unacceptable level of perceived indoor odor when a visitor enters the house.

In Chapter 4, we looked at the short-term sampling results of indoor and outdoor air pollutants like $PM_{2.5}$, BC, CO, O_3 and NO_2 in 28 low-income homes in Colorado during the wildfire seasons of 2016 and 2017. We found that even long-range wildfire plumes can significantly affect the indoor concentration of $PM_{2.5}$. The outdoor concentrations of $PM_{2.5}$ were found to be higher than indoors 59% of the time for our total sampling time. The primary source of BC in the homes were found to be infiltration from outdoor air. Outdoor BC was found to be higher than indoor concentration for 66% of the sampling time. Looking at the change in summary statistics of indoor air pollutant concentrations brought by our technique of filtering out data that were obviously caused by indoor sources, it was found that the most significant change in the concentration distribution patterns due to indoor sources was seen for $PM_{2.5}$. With respect to the distance from the closest major road, it was found that although significantly higher indoor concentration of $PM_{2.5}$, BC and CO were seen for homes located closer to a major road, there was no significant increase in indoor NO_2 for homes based on distance to the closest major road. NO_2 concentrations indoors were only significantly high in homes with gas stoves. Homes in which either a continuous MV or HRV systems were installed had significantly higher I/O ratio of $PM_{2.5}$, BC and O_3 which showed that MV systems can not only help in improving indoor air by added ventilation rates, but can also degrade it by promoting the infiltration of outdoor pollutants. Hence, air filtration is necessary in these homes, especially during the wildfire plume covers and in the homes located very close to major roads and highways.

The role of MV systems in changing indoor concentrations of BC was studied in Chapter 5 with a simulation study. Based on the characteristics of different types of MV systems, it was concluded that an HRV or ERV system integrated with the central residential HVAC system is a strategy that could not only help promote energy efficiency but also improve IAQ in low-income homes.

This dissertation provides a quantitative insight into the key building characteristics that are most important from the perspective of home ventilation in low-income households. IAQ is an often ignored and disregarded issue in low-income communities which have greater stress of basic needs as the priority. Yet, IAQ continues to affect the health and well-being of low-income communities. Government intervention programs like WAP, therefore, have a great responsibility to be cautious about the health and well-being of the home occupants besides energy efficiency improvement while systematically introducing engineering changes to the homes they live in. The learnings from this dissertation, can in fact, pave a road to future research even outside the realm of low-income housing and into middle and even high-income homes, to guide new architectural designs which treat energy efficiency and IAQ in a wholistic way. It is my sincere hope that we continue to do more extensive research in finding new ways to build healthier as well as energy-efficient buildings of the future, and find ways to better retrofit the ones that already exist.

Bibliography

[1] Residential Energy Consumption Survey (RECS) - Energy Information Administration, (n.d.). https://www.eia.gov/consumption/residential/ (accessed July 8, 2018).

[2] K. Sexton, H. Gong Jr., J.C. Bailar 3rd, J.G. Ford, D.R. Gold, W.E. Lambert, M.J. Utell, Air pollution health risks: do class and race matter?, Toxicol Ind Heal. 9 (1993) 843–878.

[3] Effects | Facts – Climate Change: Vital Signs of the Planet, (n.d.). https://climate.nasa.gov/effects/ (accessed July 8, 2018).

[4] A. Ray, J. Barsugli, K. Averyt, Climate change in Colorado: a synthesis to support water resources management and adaptation, Color. Water Conserv. Board. (2008) 1–58. http://cires.colorado.edu/websites/wwa/climate/iwcs/archive/IWCS_2008_Nov_feature.pdf.

[5] A. Rhoades, Climatology of the Intermountain West an Assessment of Temperature, Precipitation, and Snowpack in a Changing Climate Regime, (n.d.). https://watershed.ucdavis.edu/education/classes/files/content/page/4 Rhoades - Changing Precipitation %26 Temp Intermountain West.pdf (accessed July 8, 2018).

[6] L. Schipper, M. Pelling, Disaster risk, climate change and international development: scope for, and challenges to, integration, Disasters. 30 (2006) 19–38. doi:10.1111/j.1467-9523.2006.00304.x.

[7] F. Thomalla, T. Downing, E. Spanger-Siegfried, G. Han, J. Rockström, Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation, Disasters. 30 (2006) 39–48. doi:10.1111/j.1467-9523.2006.00305.x.

[8] M.M.Q. Mirza, Climate change and extreme weather events: can developing countries adapt?, Clim. Policy. 3 (2003) 233–248. doi:10.3763/cpol.2003.0330.

[9] Climate change and conflict, Polit. Geogr. 26 (2007) 627–638. doi:10.1016/J.POLGEO.2007.06.003.

[10] P.J. Gregory, J.S.I. Ingram, M. Brklacich, Climate change and food security., Philos. Trans. R. Soc. Lond. B. Biol. Sci. 360 (2005) 2139–48. doi:10.1098/rstb.2005.1745.

[11] J. Schmidhuber, F.N. Tubiello, Global food security under climate change., Proc. Natl. Acad. Sci. U. S. A. 104 (2007) 19703–8. doi:10.1073/pnas.0701976104.

[12] T. Wheeler, J. von Braun, Climate change impacts on global food security., Science. 341 (2013) 508–13. doi:10.1126/science.1239402.

[13] R.S.J. Tol, The Economic Effects of Climate Change, J. Econ. Perspect. 23 (2009) 29–51. doi:10.1257/jep.23.2.29.

[14] T.D. Prowse, C. Furgal, R. Chouinard, H. Melling, D. Milburn, S.L. Smith, Implications of Climate Change for Economic Development in Northern Canada: Energy, Resource, and Transportation Sectors, AMBIO A J. Hum. Environ. 38 (2009) 272–281. doi:10.1579/0044-7447-38.5.272.

[15] K.L. O’Brien, R.M. Leichenko, Double exposure: assessing the impacts of climate change within the context of economic globalization, Glob. Environ. Chang. 10 (2000) 221–232. doi:10.1016/S0959-3780(00)00021-2.

[16] H. Hillebrand, T. Brey, J. Gutt, W. Hagen, K. Metfies, B. Meyer, A. Lewandowska, Climate Change: Warming Impacts on Marine Biodiversity, in: Handb. Mar. Environ. Prot., Springer International Publishing, Cham, 2018: pp. 353–373. doi:10.1007/978-3-319-60156-4_18.

[17] F.J. RAHEL, J.D. OLDEN, Assessing the Effects of Climate Change on Aquatic Invasive Species, Conserv. Biol. 22 (2008) 521–533. doi:10.1111/j.1523-1739.2008.00950.x.

[18] M.A. Bhuiyan, M. Jabeen, K. Zaman, A. Khan, J. Ahmad, S.S. Hishan, The impact of climate change and energy resources on biodiversity loss: Evidence from a panel of selected Asian countries, Renew. Energy. 117 (2018) 324–340. doi:10.1016/J.RENENE.2017.10.054.

[19] Residential Energy Consumption Survey (RECS) - Energy Information Administration, (n.d.). https://www.eia.gov/consumption/residential/index.php (accessed July 8, 2018).

[20] Weatherization Assistance Program | Department of Energy, (n.d.). http://energy.gov/eere/wipo/weatherization-assistance-program.

[21] B. Tonn, D. Carroll, S. Pigg, M. Blasnik, G. Dalhoff, J. Berger, E. Rose, B. Hawkins, J. Eisenberg, F. Ucar, I. Bensch, C. Cowan, Weatherization Works-Summary of Findings from the Retrospective Evaluation of the U.S. Department of Energy’s Weatherization Assistance Program, (2014). http://www.osti.gov/scitech/ (accessed July 8, 2018).

[22] Weatherization Assistance Program | Department of Energy, (n.d.). https://www.energy.gov/eere/wipo/weatherization-assistance-program (accessed July 8, 2018).

[23] B. Stephens, E.M. Carter, E.T. Gall, C.M. Earnest, E. a. Walsh, D.E. Hun, M.C. Jackson, Home energy-efficiency retrofits, Environ. Health Perspect. 119 (2011) 283–284. doi:10.1289/ehp.1103621.

[24] B. Tonn, R. Schmoyer, S. Wagner, Weatherizing the homes of low-income home energy assistance program clients: A programmatic assessment, Energy Policy. 31 (2003) 735–744. doi:10.1016/S0301-4215(02)00124-6.

[25] J.M. Logue, M.H. Sherman, I.S. Walker, B.C. Singer, Energy impacts of envelope tightening and mechanical ventilation for the U.S. residential sector, Energy Build. 65 (2013) 281–291. doi:10.1016/j.enbuild.2013.06.008.

[26] Indoor Air Quality and Climate Readiness, US EPA, OAR, Indoor Environ. Div. (2013). http://www.epa.gov/iaq/climatereadiness/weatherization.html (accessed March 19, 2015).

[27] IOM, Climate Change , the Indoor Environment , and Health - Institute of Medicine, National Academic Press, Washington DC, 2011.

[28] W.W. Nazaroff, Exploring the consequences of climate change for indoor air quality, Environ. Res. Lett. 8 (2013) 015022. doi:10.1088/1748-9326/8/1/015022.

[29] F. Noris, G. Adamkiewicz, W.W. Delp, T. Hotchi, M. Russell, B.C. Singer, M. Spears, K. Vermeer, W.J. Fisk, Indoor environmental quality benefits of apartment energy retrofits, Build. Environ. 68 (2013) 170–178. doi:10.1016/j.buildenv.2013.07.003.

[30] S.J. Emmerich, C. Howard-reed, A. Gupte, Modeling the IAQ Impact of HHI Interventions in Inner-city Housing, Rep. U.S. Dep. Hous. Urban Dev. Off. Heal. Homes Lead Hazard Control. (2005).

[31] S.A. Bashir, Home Is Where the Harm Is: Inadequate Housing as a Public Health Crisis, Am. J. Public Health. 92 (2002) 733–738. doi:10.1300/J031v12n04_05.

[32] J. Krieger, D.L. Higgins, Housing and health: time again for public health action, J. Inf. 92 (2002) 758–769.

[33] J.S. Litt, C. Goss, L. Diao, A. Allshouse, S. Diaz-Castillo, R. a. Bardwell, E. Hendrikson, S.L. Miller, C. Di Guiseppi, Housing environments and child health conditions among recent Mexican immigrant families: A population-based study, J. Immigr. Minor. Heal. 12 (2010) 617–625. doi:10.1007/s10903-009-9261-8.

[34] IOM, Clearing the Air: Asthma and Indoor Air Exposures, National Academic Press, Washington DC, 2000.

[35] X. Yue, L.J. Mickley, J. a. Logan, J.O. Kaplan, Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century, Atmos. Environ. 77 (2013) 767–780. doi:10.1016/j.atmosenv.2013.06.003.

[36] a L. Westerling, H.G. Hidalgo, D.R. Cayan, T.W. Swetnam, Warming and earlier spring increase western U.S. forest wildfire activity., Science. 313 (2006) 940–943. doi:10.1126/science.1128834.

[37] D. V. Spracklen, L.J. Mickley, J. a. Logan, R.C. Hudman, R. Yevich, M.D. Flannigan, a. L. Westerling, Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States, J. Geophys. Res. Atmos. 114 (2009) 1–17. doi:10.1029/2008JDO10966.

[38] N. Künzli, E. Avol, J. Wu, W.J. Gauderman, E. Rappaport, J. Millstein, J. Bennion, R. McConnell, F.D. Gilliland, K. Berhane, F. Lurmann, A. Winer, J.M. Peters, Health effects of the 2003 Southern California wildfires on children, Am. J. Respir. Crit. Care Med. 174 (2006) 1221–1228. doi:10.1164/rccm.200604-519OC.

[39] J. a. Mott, D.M. Mannino, C.J. Alverson, A. Kiyu, J. Hashim, T. Lee, K. Falter, S.C. Redd, Cardiorespiratory hospitalizations associated with smoke exposure during the 1997

Southeast Asian forest fires, Int. J. Hyg. Environ. Health. 208 (2005) 75–85. doi:10.1016/j.ijheh.2005.01.018.

[40] E.R. Sutherland, B.J. Make, S. Vedal, L. Zhang, S.J. Dutton, J.R. Murphy, P.E. Silkoff, Wildfire smoke and respiratory symptoms in patients with chronic obstructive pulmonary disease, J. Allergy Clin. Immunol. 115 (2005) 420–422. doi:10.1016/j.jaci.2004.11.025.

[41] Wildfire Mitigation - Colorado State Forest Service, (n.d.). https://csfs.colostate.edu/wildfire-mitigation/ (accessed July 30, 2018).

[42] F. Collins, F.M. Offices, D. Fort, M. Field, Colorado State Forest Service, (2016) 1–8.

[43] National Report of Wildland Fires and Acres Burned by State, Natl. Interag. Fire Cent. (2014). http://www.predictiveservices.nifc.gov/intelligence/2012_statssumm/fires_acres.pdf (accessed March 13, 2015).

[44] 2012 U.S. Wildfires Statistics, (2012). http://wildland-fires.findthedata.com/l/53/2012 (accessed March 13, 2015).

[45] B. Tonn, R. Schmoyer, S. Wagner, Weatherizing the homes of low-income home energy assistance program clients: a programmatic assessment, Energy Policy. 31 (2003) 735–744. doi:10.1016/S0301-4215(02)00124-6.

[46] A. Sapkota, J.M. Symons, J. Kleissl, L. Wang, M.B. Parlange, J. Ondov, P.N. Breysse, G.B. Diette, P. a Eggleston, T.J. Buckley, Impact of the 2002 Canadian forest fires on particulate matter air quality in Baltimore city., Environ. Sci. Technol. 39 (2005) 24–32. doi:10.1021/es035311z.

[47] H.C. Phuleria, Air quality impacts of the October 2003 Southern California wildfires, J. Geophys. Res. 110 (2005) 1–11. doi:10.1029/2004JD004626.

[48] D.E. Henderson, J.B. Milford, S.L. Miller, Prescribed burns and wildfires in Colorado: impacts of mitigation measures on indoor air particulate matter., J. Air Waste Manag. Assoc. 55 (2005) 1516–1526. doi:10.1080/10473289.2005.10464746.

[49] L. Øie, P. Nafstad, G. Botten, P. Magnus, J.K. Jakkola, Ventilation in Homes and Bronchial Obstruction in Young Children.pdf, Epidemiology. 10 (1999) 294–299.

[50] M.H. Sherman, D.J. Dickerhoff, Airtightness of U.S. dwellings, ASHRAE Trans. 104 (1998) 1359–1367.

[51] J.M. Logue, P.N. Price, M.H. Sherman, B.C. Singer, A Method to Estimate the Chronic Health Impact of Air Pollutants, Environ. Health Perspect. 120 (2012) 216–222. doi:10.1289/ehp.1104035.

[52] I. Turiel, C.D. Hollowell, R.R. Miksch, J.V. Rudy, R.A. Young, M.J. Coye, The Effects of Reduced Ventilation on Indoor Air Quality in an Office Building, Atmos. Environ. 17 (1983) 51–64. doi:10.1016/0004-6981(83)90007-0.

[53] M.J. Finnegan, C. a Pickering, P.S. Burge, The sick building syndrome: prevalence studies., Br. Med. J. (Clin. Res. Ed). 289 (1984) 1573–1575.

doi:http://dx.doi.org/10.1136/bmj.289.6458.1573.

[54] J. Wilson, S.L. Dixon, D.E. Jacobs, J. Breysse, J. Akoto, E. Tohn, M. Isaacson, A. Evens, Y. Hernandez, Watts-to-Wellbeing: Does residential energy conservation improve health?, Energy Effic. 7 (2013) 151–160. doi:10.1007/s12053-013-9216-8.

[55] E. Sterling, T. Sterling, D. McIntyre, New health hazards in sealed buildings, Am. Inst. Arch. J.; (United States). 72:4 (1983). http://www.osti.gov/scitech/biblio/5395651 (accessed March 17, 2015).

[56] K. Engvall, C. Norrby, D. Norbäck, Ocular, nasal, dermal and respiratory symptoms in relation to heating, ventilation, energy conservation, and reconstruction of older multi-family houses., Indoor Air. 13 (2003) 206–211. doi:10.1034/j.1600-0668.2003.00174.x.

[57] L. Øie, L.G. Hersoug, J.Ø. Madsen, Residential exposure to plasticizers and its possible role in the pathogenesis of asthma, Environ. Health Perspect. 105 (1997) 972–978. doi:10.1289/ehp.97105972.

[58] J. Breysse, D.E. Jacobs, W. Weber, S. Dixon, C. Kawecki, S. Aceti, J. Lopez, Health outcomes and green renovation of affordable housing., Public Health Rep. 126 Suppl (2011) 64–75.

[59] Weatherization Assistance Program | Department of Energy, (n.d.). https://www.energy.gov/eere/wipo/weatherization-assistance-program (accessed May 16, 2018).

[60] J. Sundell, H. Levin, W.W. Nazaroff, W.S. Cain, W.J. Fisk, D.T. Grimsrud, F. Gyntelberg, Y. Li, A.K. Persily, A.C. Pickering, J.M. Samet, J.D. Spengler, S.T. Taylor, C.J. Weschler, Ventilation rates and health: Multidisciplinary review of the scientific literature, Indoor Air. 21 (2011) 191–204. doi:10.1111/j.1600-0668.2010.00703.x.

[61] T. Godish, J.D. Spengler, Relationships Between Ventilation and Indoor Air Quality: A Review, Indoor Air. 6 (1996) 135–145. doi:10.1111/j.1600-0668.1996.00010.x.

[62] M.J. Mendell, Non-Specific Symptoms In Office Workers: A Review And Summary Of The Epidemiologic Literature, Indoor Air. 3 (1993) 227–236. doi:10.1111/j.1600-0668.1993.00003.x.

[63] D. Menzies, J. Bourbeau, Building-Related Illnesses, N. Engl. J. Med. 337 (1997) 1524–1531. doi:10.1056/NEJM199711203372107.

[64] O. Seppänen, W.J. Fisk, Q. Lei, VENTILATION AND PERFORMANCE IN OFFICE WORK, Indoor Air J. 18 (2006) 28–36. https://pdfs.semanticscholar.org/4889/44debb027af93cb25f5741b38a8fe7fea626.pdf (accessed April 19, 2018).

[65] P. Wargocki, IMPROVING INDOOR AIR QUALITY IMPROVES THE PERFORMANCE OF OFFICE WORK AND SCHOOLWORK, (n.d.). http://www.inive.org/members_area/medias/pdf/Inive%5CIAQVEC2007%5CWargocki_2.pdf (accessed April 19, 2018).

[66] P.W. Francisco, D.E. Jacobs, L. Targos, S.L. Dixon, J. Breysse, W. Rose, S. Cali, Ventilation, indoor air quality, and health in homes undergoing weatherization, Indoor Air. 27 (2017) 463–477. doi:10.1111/ina.12325.

[67] J. Manuel, Avoiding health pitfalls of home energy-efficiency retrofits., Environ. Health Perspect. 119 (2011) A76-9. doi:10.1289/ehp.119-a76.

[68] C.Y.H. Chao, T.C.W. Tung, J. Burnett, Influence of ventilation on indoor radon level, Build. Environ. 32 (1997) 527–534. doi:10.1016/S0360-1323(97)00017-6.

[69] P.W. Francisco, D.E. Jacobs, L. Targos, S.L. Dixon, J. Breysse, W. Rose, S. Cali, Ventilation, indoor air quality, and health in homes undergoing weatherization, Indoor Air. 27 (2017) 463–477. doi:10.1111/ina.12325.

[70] S.C. Doll, E.L. Davison, B.R. Painting, Weatherization impacts and baseline indoor environmental quality in low income single-family homes, Build. Environ. 107 (2016) 181–190. doi:10.1016/J.BUILDENV.2016.06.021.

[71] S. Pigg, D. Cautley, P.W. Francisco, Impacts of weatherization on indoor air quality: A field study of 514 homes, Indoor Air. 28 (2018) 307–317. doi:10.1111/ina.12438.

[72] V. Loftness, B. Hakkinen, O. Adan, A. Nevalainen, Elements that contribute to healthy building design., Environ. Health Perspect. 115 (2007) 965–70. doi:10.1289/ehp.8988.

[73] C. Rode, M. Abadie, M. Qin, J. Grunewald, J. Kolarik, J. Laverge, IEA Project on Indoor Air Quality Design and Control in Low Energy Residential Buildings, (2016). http://orbit.dtu.dk/ws/files/127948724/paper_723.pdf (accessed May 16, 2018).

[74] A. Steinemann, P. Wargocki, B. Rismanchi, Ten questions concerning green buildings and indoor air quality, Build. Environ. 112 (2017) 351–358. doi:10.1016/J.BUILDENV.2016.11.010.

[75] Á. Broderick, M. Byrne, S. Armstrong, J. Sheahan, A.M. Coggins, A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing, Build. Environ. 122 (2017) 126–133. doi:10.1016/j.buildenv.2017.05.020.

[76] S.C. Doll, E.C. Stokes, B.E. Davis, What Are People Breathing: Impact of weatherization in low-income housing, (n.d.). https://www.isiaq.org/docs/PDF Docs for Proceedings/5A.5.pdf (accessed May 17, 2018).

[77] Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method, (1986) 1–13. http://publications.gc.ca/collections/collection_2017/ongc-cgsb/P29-149-010-M86-1986-eng.pdf (accessed April 19, 2018).

[78] M.H. Sherman, Estimation of infiltration from leakage and climate indicators, Energy Build. 10 (1987) 81–86. doi:10.1016/0378-7788(87)90008-9.

[79] The Energy Conservatory, TECTITE 4.0, (n.d.). http://energyconservatory.com/products/product/tectite/ (accessed April 20, 2018).

[80] L. Palmiter, T. Bond, Interaction of mechanical systems and natural infiltration, in: 12th

AIVC Conf., Ottawa, 1991: pp. 285–295.

[81] T. Ben-David, M.S. Waring, Impact of natural versus mechanical ventilation on simulated indoor air quality and energy consumption in offices in fourteen U.S. cities, Build. Environ. 104 (2016) 320–336. doi:10.1016/J.BUILDENV.2016.05.007.

[82] G. Bowatte, C.J. Lodge, L.D. Knibbs, A.J. Lowe, B. Erbas, M. Dennekamp, G.B. Marks, G. Giles, S. Morrison, B. Thompson, P.S. Thomas, J. Hui, J.L. Perret, M.J. Abramson, H. Walters, M.C. Matheson, S.C. Dharmage, Traffic-related air pollution exposure is associated with allergic sensitization, asthma, and poor lung function in middle age., J. Allergy Clin. Immunol. 139 (2017) 122–129.e1. doi:10.1016/j.jaci.2016.05.008.

[83] T. Schikowski, D. Sugiri, U. Ranft, U. Gehring, J. Heinrich, H.-E. Wichmann, U. Krämer, Long-term air pollution exposure and living close to busy roads are associated with COPD in women, Respir. Res. 6 (2005) 152. doi:10.1186/1465-9921-6-152.

[84] H.K. Carlsen, L. Modig, A. Levinsson, J.-L. Kim, K. Toren, F. Nyberg, A.-C. Olin, Exposure to traffic and lung function in adults: a general population cohort study, BMJ Open. 5 (2015) e007624. doi:10.1136/bmjopen-2015-007624.

[85] IECC climate zone map | Building America Solution Center, (n.d.). https://basc.pnnl.gov/images/iecc-climate-zone-map (accessed May 22, 2018).

[86] A.C.K. Lai, K.W. Mui, L.T. Wong, L.Y. Law, An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings, Energy Build. 41 (2009) 930–936. doi:10.1016/J.ENBUILD.2009.03.016.

[87] M. Sherman, D. Dickerhoff, AIR-TIGHTNESS OF U.S. DWELLINGS *, (n.d.). https://www.researchgate.net/profile/Max_Sherman/publication/279541267_Airtightness_of_US_dwellings/links/55c26ad108aebc967defdcd8/Airtightness-of-US-dwellings.pdf (accessed July 20, 2018).

[88] Meeting the Air Leakage Requirements of the 2012 IECC The newest edition of the International Energy Conservation Code ® (IECC), (n.d.). https://www.energycodes.gov/sites/default/files/documents/BECP_Buidling Energy Code Resource Guide Air Leakage Guide_Sept2011_v00_lores.pdf (accessed July 21, 2018).

[89] ASHRAE 119:1988 (R2004) | Air Leakage Performance For ... | SAI Global, (n.d.). https://infostore.saiglobal.com/en-us/standards/ashrae-119-1988-r2004--951061/ (accessed July 21, 2018).

[90] W.R. Chan, P.N. Price, M.D. Sohn, A.J. Gadgil, Analysis of U.S. Residential Air Leakage Database, (2003). https://escholarship.org/uc/item/6pk6r4gs (accessed July 11, 2018).

[91] F. Antretter, A. Karagiozis, A. Tenwolde, A. Holm, Effects of Air Leakage of Residential Buildings in Mixed and Cold Climates, (2007). https://www.fpl.fs.fed.us/documnts/pdf2007/fpl_2007_antretter001.pdf (accessed July 21, 2018).

[92] A.J. Tiberio, P. Branchi, A study of air leakage in residential buildings, in: 2013 Int. Conf. New Concepts Smart Cities Foster. Public Priv. Alliances, IEEE, 2013: pp. 1–4.

doi:10.1109/SmartMILE.2013.6708180.

[93] W.R. Chan, W.W. Nazaroff, P.N. Price, M.D. Sohn, A.J. Gadgil, Analyzing a database of residential air leakage in the United States, Atmos. Environ. 39 (2005) 3445–3455. doi:10.1016/J.ATMOSENV.2005.01.062.

[94] J. Cummings, J. Tooley, … N.M.-P. 1990 A., undefined 1990, Impacts of duct leakage on infiltration rates, space conditioning energy use, and peak electrical demand in Florida homes, Fsec.Ucf.Edu. (n.d.). http://www.fsec.ucf.edu/en/publications/html/fsec-pf-217-96/ (accessed July 20, 2018).

[95] A.K. Persily, Tracer Gas Techniques for Studying Building Air Exchange, (1988). https://www.gpo.gov/fdsys/pkg/GOVPUB-C13-57559f5109827545165a12a9e8d13414/pdf/GOVPUB-C13-57559f5109827545165a12a9e8d13414.pdf (accessed June 29, 2018).

[96] A. Barberán, R.R. Dunn, B.J. Reich, K. Pacifici, E.B. Laber, H.L. Menninger, J.M. Morton, J.B. Henley, J.W. Leff, S.L. Miller, N. Fierer, The ecology of microscopic life in household dust., Proceedings. Biol. Sci. 282 (2015) 20151139. doi:10.1098/rspb.2015.1139.

[97] H.P. Hynes, D. Brugge, N.-D. Osgood, J. Snell, J. Vallarino, J. Spengler, "Where Does the Damp Come from?" Investigations into the Indoor Environment and Respiratory Health in Boston Public Housing, J. Public Health Policy. 24 (2003) 401. doi:10.2307/3343385.

[98] K. Adachi, Y. Tainosho, Characterization of heavy metal particles embedded in tire dust, Environ. Int. 30 (2004) 1009–1017. doi:10.1016/J.ENVINT.2004.04.004.

[99] N. Pérez, J. Pey, M. Cusack, C. Reche, X. Querol, A. Alastuey, M. Viana, Variability of Particle Number, Black Carbon, and PM10, PM2.5, and PM1 Levels and Speciation: Influence of Road Traffic Emissions on Urban Air Quality, Aerosol Sci. Technol. 44 (2010) 487–499. doi:10.1080/02786821003758286.

[100] N.E. KLEPEIS, W.C. NELSON, W.R. OTT, J.P. ROBINSON, A.M. TSANG, P. SWITZER, J. V BEHAR, S.C. HERN, W.H. ENGELMANN, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Sci. Environ. Epidemiol. 11 (2001) 231–252. doi:10.1038/sj.jea.7500165.

[101] D.-L. Liu, W.W. Nazaroff, Particle Penetration Through Building Cracks, Aerosol Sci. Technol. 37 (2003) 565–573. doi:10.1080/02786820300927.

[102] D.-L. Liu, W.W. Nazaroff, Modeling pollutant penetration across building envelopes, Atmos. Environ. 35 (2001) 4451–4462. doi:10.1016/S1352-2310(01)00218-7.

[103] *,† Christopher M. Long, ‡ Helen H. Suh, § and Paul J. Catalano, P. Koutrakis‡, Using Time- and Size-Resolved Particulate Data To Quantify Indoor Penetration and Deposition Behavior, (2001). doi:10.1021/ES001477D.

[104] D.E. Henderson, J.B. Milford, S.L. Miller, Prescribed burns and wildfires in Colorado: impacts of mitigation measures on indoor air particulate matter., J. Air Waste Manag.

Assoc. 55 (2005) 1516–1526. doi:10.1080/10473289.2005.10464746.

[105] D.E. Henderson, J.B. Milford, S.L. Miller, Prescribed Burns and Wildfires in Colorado: Impacts of Mitigation Measures on Indoor Air Particulate Matter, J. Air Waste Manage. Assoc. 55 (2005) 1516–1526. doi:10.1080/10473289.2005.10464746.

[106] P. Barn, T. Larson, M. Noullett, S. Kennedy, R. Copes, M. Brauer, Infiltration of forest fire and residential wood smoke: an evaluation of air cleaner effectiveness, J. Expo. Sci. Environ. Epidemiol. 18 (2008) 503–511. doi:10.1038/sj.jes.7500640.

[107] W.J. Fisk, W.R. Chan, Health benefits and costs of filtration interventions that reduce indoor exposure to PM2.5 during wildfires, Indoor Air. 27 (2017) 191–204. doi:10.1111/ina.12285.

[108] P.K. Barn, C.T. Elliott, R.W. Allen, T. Kosatsky, K. Rideout, S.B. Henderson, Portable air cleaners should be at the forefront of the public health response to landscape fire smoke, Environ. Heal. 15 (2016) 116. doi:10.1186/s12940-016-0198-9.

[109] T. SCHOENNAGEL, T.T. VEBLEN, W.H. ROMME, The Interaction of Fire, Fuels, and Climate across Rocky Mountain Forests, Bioscience. 54 (2004) 661. doi:10.1641/0006-3568(2004)054[0661:TIOFFA]2.0.CO;2.

[110] A.L. Westerling, H.G. Hidalgo, D.R. Cayan, T.W. Swetnam, Warming and earlier spring increase Western U.S. forest wildfire activity, Science (80-.). 313 (2006) 940–943. doi:10.1126/science.1128834.

[111] A. Baccarelli, I. Martinelli, V. Pegoraro, S. Melly, P. Grillo, A. Zanobetti, L. Hou, P.A. Bertazzi, P.M. Mannucci, J. Schwartz, Living near major traffic roads and risk of deep vein thrombosis, Circulation. 119 (2009) 3118–3124. doi:10.1161/CIRCULATIONAHA.108.836163.

[112] G. Hoek, B. Brunekreef, S. Goldbohm, P. Fischer, P.A. Van Den Brandt, Association between mortality and indicators of traffic-related air pollution in the Netherlands: A cohort study, Lancet. 360 (2002) 1203–1209. doi:10.1016/S0140-6736(02)11280-3.

[113] J. Hitchins, L. Morawska, R. Wolff, D. Gilbert, Concentrations of submicrometre particles from vehicle emissions near a major road, Atmos. Environ. 34 (2000) 51–59. doi:10.1016/S1352-2310(99)00304-0.

[114] D.J. Briggs, C. de Hoogh, J. Gulliver, J. Wills, P. Elliott, S. Kingham, K. Smallbone, A regression-based method for mapping traffic-related air pollution: application and testing in four contrasting urban environments, Sci. Total Environ. 253 (2000) 151–167. doi:10.1016/S0048-9697(00)00429-0.

[115] L. Schweitzer, J. Zhou, Neighborhood Air Quality, Respiratory Health, and Vulnerable Populations in Compact and Sprawled Regions, J. Am. Plan. Assoc. 76 (2010) 363–371. doi:10.1080/01944363.2010.486623.

[116] 2008 8-Hour Ozone Standard State Implementation Plan (SIP) Control Strategy Evaluation Effort |, (n.d.). http://raqc.org/2008-8-hour-ozone-standard-state-implementation-plan-sip-control-strategy-evaluation-effort/ (accessed July 10, 2018).

[117] S. Miller, N. Facciola, D. Toohey, J. Zhai, Ultrafine and Fine Particulate Matter Inside and Outside of Mechanically Ventilated Buildings, Int. J. Environ. Res. Public Health. 14 (2017) 128. doi:10.3390/ijerph14020128.

[118] R.J. Laumbach, Outdoor air pollutants and patient health., Am. Fam. Physician. 81 (2010) 175–80. http://www.ncbi.nlm.nih.gov/pubmed/20082513 (accessed July 11, 2018).

[119] P.M. Bluyssen, E. Oliveira Fernandes, L. Groes, G. Clausen, P.O. Fanger, O. Valbjorn, C.A. Bernhard, C.A. Roulet, European Indoor Air Quality Audit Project in 56 Office Buildings, Indoor Air. 6 (1996) 221–238. doi:10.1111/j.1600-0668.1996.00002.x.

[120] H. Fromme, J. Diemer, S. Dietrich, J. Cyrys, J. Heinrich, W. Lang, M. Kiranoglu, D. Twardella, Chemical and morphological properties of particulate matter (PM10, PM2.5) in school classrooms and outdoor air, Atmos. Environ. 42 (2008) 6597–6605. doi:10.1016/J.ATMOSENV.2008.04.047.

[121] I. Rivas, M. Viana, T. Moreno, M. Pandolfi, F. Amato, C. Reche, L. Bouso, M. Àlvarez-Pedrerol, A. Alastuey, J. Sunyer, X. Querol, Child exposure to indoor and outdoor air pollutants in schools in Barcelona, Spain, Environ. Int. 69 (2014) 200–212. doi:10.1016/J.ENVINT.2014.04.009.

[122] A. Haines, R.S. Kovats, D. Campbell-Lendrum, C. Corvalan, Climate change and human health: Impacts, vulnerability and public health, Public Health. 120 (2006) 585–596. doi:10.1016/j.puhe.2006.01.002.

[123] M.S. O’Neill, M. Jerrett, I. Kawachi, J.I. Levy, A.J. Cohen, N. Gouveia, P. Wilkinson, T. Fletcher, L. Cifuentes, J. Schwartz, T.F. Bateson, C. Cann, D. Dockery, D. Gold, F. Laden, S. London, D. Loomis, F. Speizer, S. Van den Eeden, A. Zanobetti, Health, wealth, and air pollution: Advancing theory and methods, Environ. Health Perspect. 111 (2003) 1861–1870. doi:10.1289/ehp.6334.

[124] Boulder Housing Partners | Boulder Housing Partners, (n.d.). https://www.boulderhousing.org/ (accessed June 12, 2018).

[125] MODEL 3 MINNEAPOLIS BLOWER DOOR^{TM}, (n.d.). http://energyconservatory.com/wp-content/uploads/2017/08/Blower-Door-Overview-Booklet.pdf (accessed July 10, 2018).

[126] S. Steinle, S. Reis, C.E. Sabel, S. Semple, M.M. Twigg, C.F. Braban, S.R. Leeson, M.R. Heal, D. Harrison, C. Lin, H. Wu, Personal exposure monitoring of PM 2.5 in indoor and outdoor microenvironments, Sci. Total Environ. 508 (2014) 383–394. doi:10.1016/j.scitotenv.2014.12.003.

[127] microAeth® / AE51 | AethLabs, (n.d.). https://aethlabs.com/microaeth/ae51/tech-specs (accessed July 10, 2018).

[128] C.H. Yu, M.T. Morandi, C.P. Weisel, Passive dosimeters for nitrogen dioxide in personal/indoor air sampling: a review., J. Expo. Sci. Environ. Epidemiol. 18 (2008) 441–51. doi:10.1038/jes.2008.22.

[129] 1405-F TEOM^{TM} Continuous

Ambhttp://www.thermofisher.com/order/catalog/product/75003424ient Air Monitor, (n.d.). https://www.thermofisher.com/order/catalog/product/TEOM1405F (accessed July 10, 2018).

[130] G.S.W. Hagler, T.L.B. Yelverton, R. Vedantham, A.D.A. Hansen, J.R. Turner, Post-processing Method to Reduce Noise while Preserving High Time Resolution in Aethalometer Real-time Black Carbon Data, Aerosol Air Qual. Res. 11 (2011) 539–546. doi:10.4209/aaqr.2011.05.0055.

[131] Pod Technology | Hannigan Air Quality and Technology Research Lab | University of Colorado Boulder, (n.d.). https://www.colorado.edu/lab/hannigan/pod-technology (accessed April 13, 2018).

[132] R. Piedrahita, Y. Xiang, N. Masson, J. Ortega, A. Collier, Y. Jiang, K. Li, R.P. Dick, Q. Lv, M. Hannigan, L. Shang, The next generation of low-cost personal air quality sensors for quantitative exposure monitoring, Atmos. Meas. Tech. 7 (2014) 3325–3336. doi:10.5194/amt-7-3325-2014.

[133] CDPHE - Colorado.gov/AirQuality, (n.d.). https://www.colorado.gov/airquality/site_description.aspx (accessed April 20, 2018).

[134] J.J. Cao, S.C. Lee, J.C. Chow, Y. Cheng, K.F. Ho, K. Fung, S.X. Liu, J.G. Watson, Indoor/outdoor relationships for PM2.5 and associated carbonaceous pollutants at residential homes in Hong Kong - case study, Indoor Air. 15 (2005) 197–204. doi:10.1111/j.1600-0668.2005.00336.x.

[135] R. Allen, T. Larson, L. Sheppard, L. Wallace, L.-J.S. Liu, Use of Real-Time Light Scattering Data To Estimate the Contribution of Infiltrated and Indoor-Generated Particles to Indoor Air, Environ. Sci. Technol. 37 (2003) 3484–3492. doi:10.1021/es021007e.

[136] G. Ramachandran, J.L. Adgate, N. Hill, K. Sexton, G.C. Pratt, D. Bock, Comparison of Short-Term Variations (15- Minute Averages) in Outdoor and Indoor PM 2.5 Concentrations Comparison of Short-Term Variations (15-Minute Averages) in Outdoor and Indoor PM 2.5 Concentrations, J. Air Waste Manag. Assoc. J. J. Air Waste Manag. Assoc. J. Air Waste Manag. Assoc. J. Air Waste Manag. Assoc. 507 (2000) 1096–2247. doi:10.1080/10473289.2000.10464160.

[137] M.H. GARRETT, M.A. HOOPER, B.M. HOOPER, M.J. ABRAMSON, Respiratory Symptoms in Children and Indoor Exposure to Nitrogen Dioxide and Gas Stoves, Am. J. Respir. Crit. Care Med. 158 (1998) 891–895. doi:10.1164/ajrccm.158.3.9701084.

[138] D.W. Dockery, J.D. Spengler, M.P. Reed, J. Ware, Relationships among personal, indoor and outdoor NO2 measurements, Environ. Int. 5 (1981) 101–107. doi:10.1016/0160-4120(81)90129-X.

[139] T.P. Ng, K.P. Hui, W.C. Tan, Respiratory symptoms and lung function effects of domestic exposure to tobacco smoke and cooking by gas in non-smoking women in Singapore., J. Epidemiol. Community Health. 47 (1993) 454–8. doi:10.1136/JECH.47.6.454.

[140] U.D. of C.N.N.E.S.D. and I.S.O. of S. and P. Operations, NOAA's Office of Satellite and

Product Operations, (n.d.). http://www.ospo.noaa.gov/Products/land/hms.html (accessed April 13, 2018).

[141] B.N. Duncan, A.I. Prados, L.N. Lamsal, Y. Liu, D.G. Streets, P. Gupta, E. Hilsenrath, R.A. Kahn, J.E. Nielsen, A.J. Beyersdorf, S.P. Burton, A.M. Fiore, J. Fishman, D.K. Henze, C.A. Hostetler, N.A. Krotkov, P. Lee, M. Lin, S. Pawson, G. Pfister, K.E. Pickering, R.B. Pierce, Y. Yoshida, L.D. Ziemba, Satellite data of atmospheric pollution for U.S. air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid, Atmos. Environ. 94 (2014) 647–662. doi:10.1016/j.atmosenv.2014.05.061 Review.

[142] Data Catalog: Online Transportation Information System, Colorado Department of Transportation, (n.d.). http://dtdapps.coloradodot.info/otis/catalog (accessed July 10, 2018).

[143] N. Rose, C. Cowie, R. Gillett, G.B. Marks, Weighted road density: A simple way of assigning traffic-related air pollution exposure, Atmos. Environ. 43 (2009) 5009–5014. doi:10.1016/J.ATMOSENV.2009.06.049.

[144] T. Schikowski, D. Sugiri, U. Ranft, U. Gehring, J. Heinrich, H.-E. Wichmann, U. Krämer, Long-term air pollution exposure and living close to busy roads are associated with COPD in women, Respir. Res. 6 (2005) 152. doi:10.1186/1465-9921-6-152.

[145] G. Bowatte, B. Erbas, C.J. Lodge, L.D. Knibbs, L.C. Gurrin, G.B. Marks, P.S. Thomas, D.P. Johns, G.G. Giles, J. Hui, M. Dennekamp, J.L. Perret, M.J. Abramson, E.H. Walters, M.C. Matheson, S.C. Dharmage, Traffic-related air pollution exposure over a 5-year period is associated with increased risk of asthma and poor lung function in middle age., Eur. Respir. J. 50 (2017) 1602357. doi:10.1183/13993003.02357-2016.

[146] M. Krzyżanowski, B. Kuna-Dibbert, J. Schneider, Health effects of transport-related air pollution, World Health Organization Europe, 2005. https://books.google.com/books?id=b2G3k51rd0oC&dq=Traffic-related+air+pollution:+A+critical+review+of+the+literature+on+emissions,+exposure,+and+health+effects&lr=&source=gbs_navlinks_s (accessed July 10, 2018).

[147] S.J. Dutton, J.J. Schauer, S. Vedal, M.P. Hannigan, PM2.5 characterization for time series studies: Pointwise uncertainty estimation and bulk speciation methods applied in Denver, Atmos. Environ. 43 (2009) 1136–1146. doi:10.1016/J.ATMOSENV.2008.10.003.

[148] Air Quality Technical Memorandum Southeast Extension Project Lincoln Station to RidgeGate Parkway, (2014). http://rtd-fastracks.com/media/uploads/se/SE_AirQuality_TechReport_-_0514.pdf (accessed July 11, 2018).

[149] N. Clements, P. Keady, J. Emerson, N. Fierer, S. Miller, Seasonal Variability of Airborne Particulate Matter and Bacterial Concentrations in Colorado Homes, Atmosphere (Basel). 9 (2018) 133. doi:10.3390/atmos9040133.

[150] M. Viana, S. Díez, C. Reche, Indoor and outdoor sources and infiltration processes of PM1 and black carbon in an urban environment, Atmos. Environ. 45 (2011) 6359–6367.

doi:10.1016/J.ATMOSENV.2011.08.044.

[151] S.M. Relwani, D.J. Moschandreas, I.H. Billick, Effects of Operational Factors on Pollutant Emission Rates from Residential Gas Appliances, J. Air Pollut. Control Assoc. 36 (1986) 1233–1237. doi:10.1080/00022470.1986.10466170.

[152] K. Lee, J.I. Levy, Y. Yanagisawa, J.D. Spengler, I.H. Billick, The Boston Residential Nitrogen Dioxide Characterization Study: Classification and Prediction of Indoor NO $_2$ Exposure, J. Air Waste Manage. Assoc. 48 (1998) 736–742. doi:10.1080/10473289.1998.10463717.

[153] N.L. Gilbert, S. Woodhouse, D.M. Stieb, J.R. Brook, Ambient nitrogen dioxide and distance from a major highway, Sci. Total Environ. 312 (2003) 43–46. doi:10.1016/S0048-9697(03)00228-6.

[154] C. Granier, G.P. Brasseur, The impact of road traffic on global tropospheric ozone, Geophys. Res. Lett. 30 (2003). doi:10.1029/2002GL015972.

[155] E.D. Thoma, R.C. Shores, V. Isakov, R.W. Baldauf, Characterization of Near-Road Pollutant Gradients Using Path-Integrated Optical Remote Sensing, J. Air Waste Manage. Assoc. 58 (2008) 879–890. doi:10.3155/1047-3289.58.7.879.

[156] K. ZAYASU, K. SEKIZAWA, S. OKINAGA, M. YAMAYA, T. OHRUI, H. SASAKI, Increased Carbon Monoxide in Exhaled Air of Asthmatic Patients, Am. J. Respir. Crit. Care Med. 156 (1997) 1140–1143. doi:10.1164/ajrccm.156.4.96-08056.

[157] Whole-House Ventilation | Department of Energy, (n.d.). https://www.energy.gov/energysaver/weatherize/ventilation/whole-house-ventilation (accessed July 5, 2018).

[158] Technically Speaking: Whole-House Mechanical Ventilation | Building Performance Institute, (n.d.). http://www.bpihomeowner.org/blog/technically-speaking-whole-house-mechanical-ventilation (accessed July 11, 2018).

[159] H. Sherman, Estimation of Infiltration from leakage and Climate Indicators, Energy Build. 10 (1987) 81–86. https://escholarship.org/uc/item/7n25v6kd (accessed July 11, 2018).

[160] J.L. Sublett, J. Seltzer, R. Burkhead, P.B. Williams, H.J. Wedner, W. Phipatanakul, Air filters and air cleaners: Rostrum by the American Academy of Allergy, Asthma & Immunology Indoor Allergen Committee, J. Allergy Clin. Immunol. 125 (2010) 32–38. doi:10.1016/J.JACI.2009.08.036.

[161] Products | www.fantech.net, (n.d.). http://www.fantech.net/products/residential-fresh-air-systems/fresh-air-appliances/vertical-appliances/vhr-r/flex-100h-es-fr.-air-appliance/ (accessed July 6, 2018).

[162] CONTAM | NIST, (n.d.). https://www.nist.gov/services-resources/software/contam (accessed July 6, 2018).

[163] J. Hitchins, L. Morawska, R. Wolff, D. Gilbert, Concentrations of submicrometre particles from vehicle emissions near a major road, Atmos. Environ. 34 (2000) 51–59.

doi:10.1016/S1352-2310(99)00304-0.

[164] W.S. Dols, B.J. Polidoro, CONTAM User Guide and Program Documentation Version 3.2, Gaithersburg, MD, 2015. doi:10.6028/NIST.TN.1887.

[165] M. Gysel, M. Laborde, J.S. Olfert, R. Subramanian, A.J. Gröhn, Effective density of Aquadag and fullerene soot black carbon reference materials used for SP2 calibration, Atmos. Meas. Tech. 4 (2011) 2851–2858. doi:10.5194/amt-4-2851-2011.

[166] Carbon - Specific Heat, Latent Heat of Fusion, Latent Heat of Vaporization - Nuclear Power, (n.d.). https://www.nuclear-power.net/carbon-specific-heat-latent-heat-vaporization-fusion/ (accessed July 11, 2018).