Title

Guidelines for Improving Household Indoor Air Quality: A Narrative Review and Scenario Testing Report

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Guidelines for Improving Household Indoor Air Quality: A Narrative Review and Scenario Testing Report

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by

Kiera Alexandra Dixon

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ABSTRACT OF THE THESIS

Guidelines for Improving Household Indoor Air Quality: A Narrative Review and Scenario Testing Report

by

Kiera Alexandra Dixon
Master of Science in Environmental Health Sciences
University of California, Los Angeles, 2023
Professor Yifang Zhu, Chair

As most individuals within the United States spend the majority of their time indoors at home, residential indoor air quality is an important area for mitigating exposure to toxic air pollutants. This is especially important for low-income communities who are more likely to live in polluted areas with poor housing quality and lack the resources to obtain and maintain effective mechanical and exhaust ventilation within the home. The main research objective is to provide guidelines backed by current research and modeling to determine optimal window-opening behavior for reducing overall exposure to pollutants in different residential scenarios. Available literature was used to inform the majority of scenarios in which there are predominantly indoor-only, outdoor-only, or minimal indoor and outdoor sources. However, for a complex scenario in which there are both elevated levels of indoor and outdoor pollutants and where natural ventilation or exhaust-only ventilation are the only options, the Contaminant Transport Analysis Method (CONTAM) indoor air quality model program was used to determine pollutant exposure levels under three different window-opening strategies (windows closed, windows open, and windows open temporarily). Results indicate that strategic ventilation (temporarily opening windows during and shortly after indoor source pollutant generation) can be a low-cost option for low-income residential buildings without working exhaust fans. However, the use of well-maintained and efficient exhaust fans should be prioritized while cooking. Using electric appliances can also reduce indoor pollutants and offer more flexibility in ventilation options.

The thesis of Kiera Alexandra Dixon is approved.

Rachael M. Jones

Lara J. Cushing

Yifang Zhu, Committee Chair

University of California, Los Angeles

2023

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

PM	Particulate Matter
$PM_{2.5}$	Fine Particulate Matter
NO_2	Nitrogen Dioxide
VOCs	Volatile Organic Compounds
CO_2	Carbon Dioxide
SO_2	Sulfur Dioxide
SBS	Sick Building Syndrome
US	United States
EPA	Environmental Protection Agency
NAAQS	National Ambient Air Quality Standards
WHO	World Health Organization
O_3	Ozone
SES	Socioeconomic Status
CONTAM	Contaminant Transport Analysis Method
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CDC	Centers for Disease Control and Prevention
NIST	National Institute of Standards and Technology
HVAC	Heating, Ventilation, and Air Conditioning
AQI	Air Quality Index
USG	Unhealthy for Sensitive Groups
mg	Milligram
μg	Microgram
min	Minute
m	Meter
m^3	Cubic meter

km	Kilometer
h	Hour
L	Liter
ppm	Parts per million
ppb	Parts per billion
Temp.	Temporarily
TWA	Time-Weighted Average

1. Introduction

Common indoor air pollutants are particulate matter (PM), nitrogen dioxide (NO_2), carbon monoxide, formaldehyde, and volatile organic compounds (VOCs). Indoor sources of these pollutants include cooking, smoking, cleaning, burning candles, furniture, consumer products, and building materials (Vardoulakis et al., 2020 and Modera et al., 2022). There is comprehensive and significant evidence linking adverse health effects and exposure to air pollution. Fine particulate matter ($PM_{2.5}$) is associated with respiratory illness, cardiovascular disease, and premature mortality (Anderson et al., 2012; Mukherjee and Agrawal, 2017). Exposure to NO_2 has been found to be associated with acute respiratory symptoms and adverse effects on the respiratory health of children with asthma (Vardoulakis et al., 2020). Although not a toxic pollutant at low levels, there are also negative health effects from excessive levels of carbon dioxide (CO_2) in indoor environments from occupant respiration. This is known as Sick Building Syndrome (SBS), and is characterized by headaches, nausea, and dizziness (Joshi, 2008), sometimes at levels as low as 1000 ppm (Allen et al., 2016).

Indoor air pollutant exposure has received less attention than outdoor exposure even though concentrations are significant, and people spend more time indoors. In the United States (US), individuals spend approximately 87% of their time indoors and 69% of their time at home (Klepeis et al., 2001). However, although approximately 40-60% of indoor pollutants come from indoor sources (Doll et al., 2016), neither the United States nor California have implemented indoor air quality standards. Instead, standards exist for pollutants in ambient air. The Environmental Protection Agency (EPA) outdoor $PM_{2.5}$ National Ambient Air Quality Standard (NAAQS) is currently an annual mean, averaged over three years, of 12.0 $\mu g/m^3$. The NAAQS for NO_2 is currently an annual mean of 53 ppb, or about 100 $\mu g/m^3$ (US EPA). Ambient air quality standards may be exceeded in indoor environments. One study of California apartments found four had weekly $PM_{2.5}$ above the California annual outdoor standard of 12 $\mu g/m^3$ and discrete days above the World Health Organization (WHO) 24-hour guideline of 25 µg/m^3. Two of the apartments had weekly NO_2 above the California annual outdoor standard of 30 ppb (Zhao et al., 2020).

Air quality in indoor environments is a complex process influenced by indoor sources as well as ambient pollutants that penetrate the indoor environment. Factors that influence the latter range from building characteristics, such as ventilation and leakage, to weather conditions such as wind and indoor/outdoor temperature differences (Das et al., 2014; Abdalla et al., 2021). Ventilation is key to maintaining healthy indoor air quality, as it can remove airborne pollutants from indoor air, but may also facilitate transport of pollutants from the ambient environment into the indoor environment. The three main types of ventilation in buildings are infiltration of air through small cracks and openings in the building, natural ventilation (opening windows and doors), and mechanical ventilation (Chen and Zhao, 2011). Mechanical ventilation can be split into supply only, exhaust only, and balanced (equal supply of outdoor air and exhaust of indoor air). Mechanical ventilation may or may not include filters installed to partially clean outdoor air that is brought in through the supply system (Shrestha et al., 2019; Modera et al., 2022).

Although window opening can be a simple and effective way to reduce occupant exposure to high levels of indoor air pollutants, it has the potential to increase or decrease indoor pollutant concentrations depending on the situation (Tsoulou et al., 2021). For example, Connolly et al. used low-cost sensors to evaluate window-opening on $PM_{2.5}$ concentrations in residential buildings and found opening windows significantly accelerates the drop in indoor $PM_{2.5}$ concentrations to the background level after cooking indoors, which is an effective ventilation measure to mitigate cooking-derived $PM_{2.5}$. However, the study notes that the impact of window-opening behavior on indoor air quality depends on other factors such as the ambient $PM_{2.5}$ for each given hour. The results for the tested apartments at the time indicated that opening windows is only an effective strategy for reducing indoor pollutant concentrations when ambient $PM_{2.5}$ is below a certain level (Connolly et al., 2022). There are also pollutants that are predominantly sourced from the ambient environment, like ozone (O_3). Ozone is primarily formed from photochemical reactions in the atmosphere outdoors. However, overall exposure to ozone has been found to be highly dependent on indoor concentrations (Weschler et al., 1989). Therefore, ambient pollution levels, along with other factors such as weather conditions, indoor source type, and indoor source duration of use can make it difficult for the average person to determine if, when, and for how long windows should be opened to achieve optimal indoor air quality. A 2021 study found that strategic ventilation, or opening windows for a specific small period of time, was an effective mitigation measure for maintaining optimal indoor air quality during wintertime in Swiss classrooms (Vassella et al., 2021). Similarly, when natural ventilation is combined with mechanical ventilation, known as hybrid ventilation, energy costs can be reduced while also maintaining indoor air quality (Rey-Hernandez et al., 2020; Ledo Gomis et al., 2021).

Due to the complexity of the issue, there is a need for better guidance on natural ventilation, especially in low-income neighborhoods where ventilation options are limited or cost-prohibitive and outdoor pollutant concentrations are high, posing a potential trade-off. “Poorer-quality housing (e.g., less tightly sealed windows, lack of air conditioning, and more open windows) in lower socioeconomic status (SES) areas may result in greater penetration of traffic-related pollutants indoors,” (Wilhelm and Ritz, 2003). Modera et al., 2022 expand on this issue by noting that disadvantaged communities often reside near pollution sources like highways and power plants, while low-income populations living in multifamily housing experience poor indoor air quality due to leaks between units. Therefore, improving indoor air quality in multifamily buildings is crucial to addressing environmental disparities. In recent years, California has implemented Title 24, a new requirement for whole dwelling unit ventilation, but only in newly constructed multifamily units (Chan et al., 2020). Previously, exhaust-only ventilation systems were commonly used, which relied on depressurizing the building to remove air from units and allow fresh air to infiltrate through leaks. However, concerns have been raised about the potential health and comfort issues associated with air coming from adjacent units (Modera et al., 2022). A review by Ferguson et al. in 2020 found that there was significant evidence of higher exposure to PM and NO_2 for those of lower socioeconomic status, potentially due to the higher outdoor levels, indoor smoking rates, and buildings with a reduced number of external façades with which to exchange outdoor air. In addition to being located in areas with increased outdoor pollutant levels, low-income homes tend to be older, leakier, and smaller than average (Shrestha et al., 2019; American Housing Survey, 2021). The higher amount of leakier internal façades can lead to increased inter-unit transfer of pollutants (Modera et al., 2022). Poorer housing quality can easily result in broken or inefficient kitchen exhaust fans (American Housing Survey, 2021). As shown by a recent California study, even low-income homes with mechanical ventilation are at risk of poor performance in maintaining indoor air quality (Zhao et al., 2021).

This study focuses on improved ventilation, with an emphasis on natural ventilation, as there has been no previous field or model investigation of strategic natural ventilation as a last-resort intervention in situations with elevated concentrations of indoor and outdoor pollutants. It is important to note that current guidelines typically focus on two other means of improving indoor air quality, in addition to improved ventilation. These include source reduction and air cleaning (US EPA). Interventions that recommend improved mechanical ventilation or air purifiers are limited to households with adequate resources and means. In this study, a narrative literature review was performed to condense available ventilation-related guidelines and studies relating to the maintenance of optimal indoor air quality into a flow chart under various scenarios (Figure 2). The CONTAM model was then used to simulate airflow and air pollutant exposure in a representative low-income, multi-family residential building in California to investigate the effect of opening, temporarily opening, or closing windows on indoor air quality. The reason behind the lack of specific and tailored guidance on indoor ventilation is likely in part due to the complexity and large emission rate range of various indoor sources of pollution and environmental factors that affect pollutant transfer between indoor and outdoor spaces. The results of the CONTAM simulations were used to fill in some of the gaps for currently available guidelines to determine optimal window-opening behavior during complex scenarios with both elevated outdoor and indoor pollutants and limited ventilation options (Figure 3). Overall, the guidelines aim to provide valuable insights into the factors that influence indoor air quality and can help inform decisions about the best strategies for maintaining optimal air quality in residential buildings.

CONTAM is a whole building, multizone indoor air quality and ventilation model developed by the National Institute of Standards and Technology (NIST) used to estimate airflow, contaminant concentrations, and personal exposure to pollutants in indoor air (Dols and Polidoro, 2021). CONTAM has been widely used to explore indoor air quality issues. For example, Modera et al., 2022 used the program to investigate the role of compartmentalization, or airtightness, on the inter-unit transfer of pollutants from indoor sources such as cooking and smoking. The authors found that residents within new-construction multi-family buildings in California experienced lower pollution levels from inter-unit transfer, but higher levels from reduced outdoor infiltration, which was a similar finding by Emmerich et al., 2005. Another study by Lebel et al., 2022 used CONTAM to determine household benzene levels leaking from unburned natural gas stoves. The CONTAM software was also employed to simulate $PM_{2.5}$ levels in a study involving a four-story multifamily building. The study considered three ventilation scenarios: infiltration-only (air entering through unintended openings), whole-building exhaust ventilation, and whole-building balanced supply/exhaust ventilation. The balanced ventilation system yielded the lowest $PM_{2.5}$ concentrations, followed by the whole building exhaust ventilation system (Underhill et al., 2020). These studies have used CONTAM to explore the impact of ventilation, including infiltration through the building envelope, and different mechanical ventilation systems on indoor air quality, finding that there is often a trade-off between performance and cost. Since cost can be prohibitive for many households, there is a need to explore low-cost options of natural ventilation.

There were four pollutants chosen for evaluation in this study. $PM_{2.5}$ and NO_2 were chosen because they are commonly emitted from both indoor and outdoor sources (US EPA). Specifically, indoor $PM_{2.5}$ can come from indoor sources such as cooking (food and gas stoves), smoking, and candle burning, as well as outdoor sources that infiltrate the indoor environment, such as vehicle exhaust, industrial emissions, and wildfire smoke. Indoor NO_2 can come from gas cooking, heating, and infiltrated vehicle exhaust. Predominantly indoor-generated pollutants include VOCs and formaldehyde emitted from consumer products, building materials and furniture along with CO_2 from occupant respiration. CO_2 was chosen to represent a predominant indoor pollutant and ozone was chosen to represent a predominantly outdoor-generated pollutant. These air pollutants were incorporated to provide additional context to the effects of window-opening behavior within the CONTAM simulations.

2. Methods

2.1. Narrative Literature Review

A narrative review of the literature was performed to extract key information for the compilation of previously available guidelines for residential ventilation strategies, including window-opening behavior, during various environmental conditions. The review utilized search engines, including Google Scholar, PubMed, along with Google Search to identify relevant official websites such as the EPA, American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), and the Centers for Disease Control and Prevention (CDC). Key search terms included “residential indoor air quality ventilation” paired with those summarized in Table 1. Inclusion criteria included *(a)* evidence-based guidelines, or those informed by primary literature *(b)* publication date from 2010 to 2023 *(c)* relevant to California residences *(d)* free and accessible. Potentially eligible studies were then reviewed via the inspection of the titles and/or abstracts and then read carefully to determine whether they were suitable for inclusion. Studies that did not include or inform personal, ventilation-related interventions or guidelines that are accessible for implementation by the general public for reducing exposure to indoor air pollution were excluded. In total, 26 publications or official sources were used in the narrative review.

Table 1: Search terms used in the narrative literature review.

Category	**Search Terms: Residential indoor air quality ventilation AND…**
General Background	natural OR windows OR mechanical OR exhaust fans
Official Guidelines	government OR official
Indoor Air Pollution	sick building syndrome OR carbon dioxide OR cooking OR smoking OR candle burning OR combustion OR cleaning OR $PM_{2.5}$ OR fine particulate matter OR nitrogen dioxide
Outdoor Air Pollution	wildfire OR traffic OR industry OR oil gas OR $PM_{2.5}$ OR fine particulate matter OR nitrogen dioxide OR ozone
Both Indoor and Outdoor Air Pollution	indoor AND outdoor sources
Inequities	environmental justice OR low income OR low socioeconomic status OR inequity

2.2. CONTAM Simulations

The CONTAM model was employed to simulate multiple common scenarios with natural ventilation as the intervention option. The optimal window opening intervention that would result in the lowest pollutant exposure to an indoor occupant was determined. This was achieved through comparing the time-weighted average (TWA) occupant exposure to indoor pollutant concentrations and peak indoor concentrations under always open, temporarily open, and always closed window intervention strategies for each scenario and the strategy that resulted in lower overall pollutant exposure was identified. Time-weighted average exposure to ozone (O_3) and carbon dioxide (CO_2) were also modeled to provide context for the levels of predominantly outdoor and indoor pollutants, respectively. These findings were then incorporated into the flow chart (Figure 3) to guide decision-making in these complex scenarios. Available literature was used to identify typical input factors for the CONTAM simulations that would also have a significant effect on indoor air quality. Various publications were also used as model papers for the comparison testing of window-opening intervention strategies (Emmerich et al., 2005.; Underhill et al., 2020; Modera et al., 2022). The complex and limited-ventilation scenarios involve elevated levels of both indoor and outdoor air pollution and only natural ventilation in which it is unclear whether to open or close windows to maintain optimal air quality. The factors chosen for the scope of this analysis were indoor source type, duration of indoor source emissions, kitchen exhaust fan use, and ambient air quality.

2.2.1. Simulation Configurations

CONTAM was configured to run a transient simulation for both airflows and pollutants. The default solver, Implicit Euler, which is a fixed time step solver was selected. Airflows and pollutants were simulated over four days at 1-minute timesteps. The first three days were run with no indoor pollutant source to allow the indoor/outdoor ratio of pollutant concentrations to reach equilibrium. On the fourth day, the indoor source began emitting at 18:00, a typical time for cooking dinner or smoking after work. The simulation continued until the end of the day (24:00). When calculating time-weighted average occupant exposure, contaminant results were analyzed only for the 6-hour period of the fourth day between 18:00-24:00. During cooking simulations, the occupant was scheduled to be in the kitchen from 18:00-22:00, and then the bedroom from 22:00-24:00. During smoking simulations, the occupant was scheduled to be in the living room from 18:00-22:00 and then in the bedroom from 22:00-24:00. The goal was to investigate a short time period of elevated indoor and outdoor pollutants. CONTAM provides plots of occupant exposures to indoor contaminants. These, along with the one-minute time intervals on the fourth day, were used to visualize and calculate the time-weighted average and peak exposures for an indoor occupant.

2.2.2. Typical California Low-Income Residential Setting

The National Institute of Standards and Technology (NIST) provides a database of pre-made building layouts for use in CONTAM (Case 11, NIST). Using this NIST database, one multi-family residential apartment building that was representative of the size and type of a low-income residence in the United States was chosen. The multi-family residence has a unique NIST stock ID named APT-26, which is a four-story building with four one-bedroom, one-bath units per floor, each 704 square feet/unit. To simulate natural ventilation and/or exhaust-only situations, the HVAC system was removed, and air entered the home only via infiltration or through one window in the living room or kitchen, for smoking and cooking scenarios, respectively. The preset exhaust fans in the kitchen and bathroom were retained. APT-26 was chosen as it was an older, leakier building with 8-foot ceilings according to the Persily U.S. Housing Stock paper for which the NIST floor plans were based (Figure 1 and Figure S1). Specifically, the building was made to be representative of a building built between the years 1940-1969, with a normalized leakage value of 1.03 (Table S1). Other building characteristics are summarized in Table S2. All simulations were performed on the second floor. Official historical weather records of average wind speed, temperature (outdoor and indoor), and humidity in California were used. Mild conditions were represented with a low indoor/outdoor temperature difference, low wind speed, and average humidity (Table S3). Although all of these factors play a role in the transfer of pollutants between the indoor and outdoor environments, as discussed later, these were all held constant to reduce the number of simulations so that they could be performed within a reasonable time frame.

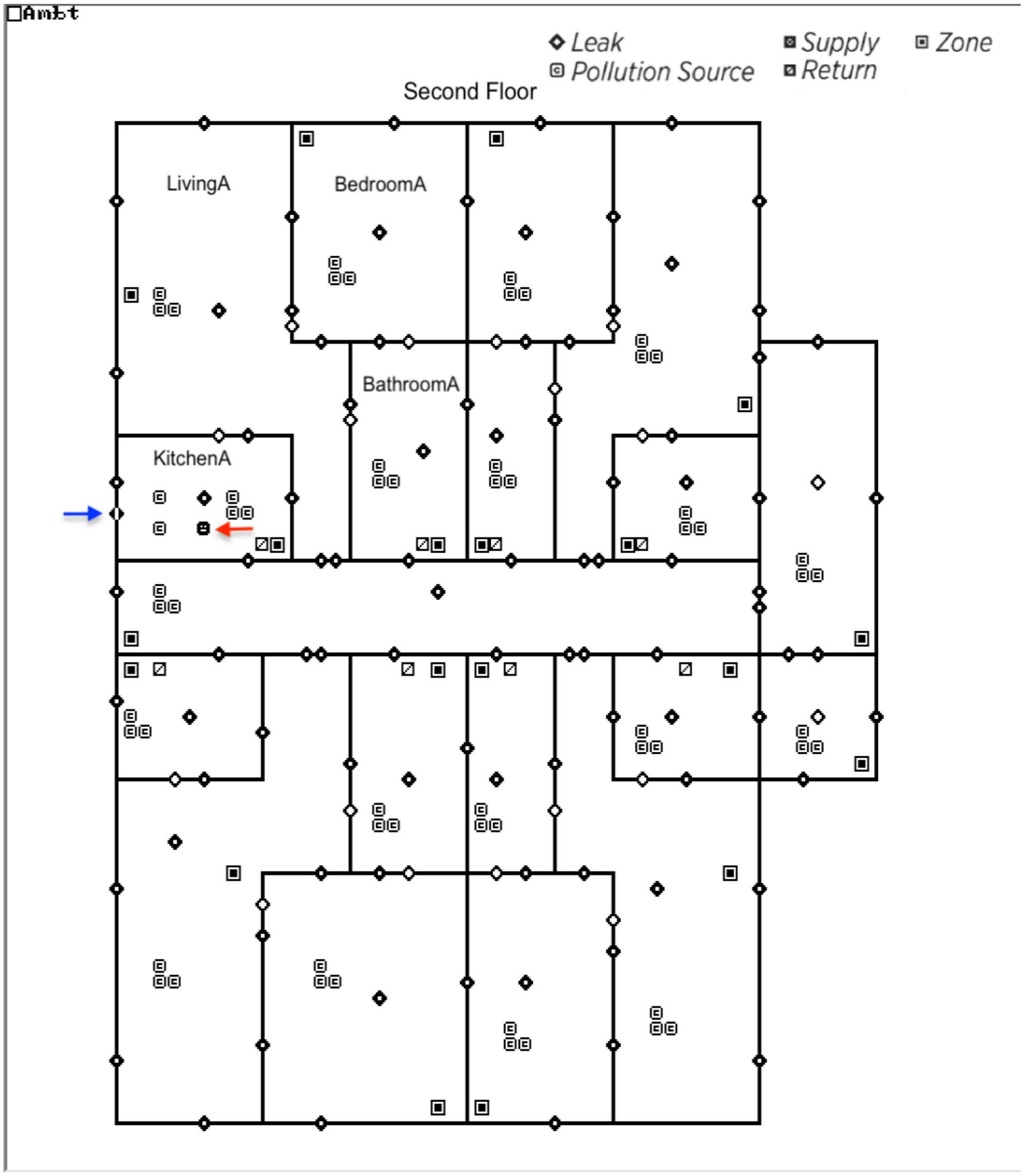


Figure 1: CONTAM floorplan showing leakage elements and pollution sources and sinks. There are two pollutants generated, NO2 and PM2.5 in KitchenA. The three grouped "Pollution Sources" within every zone are the continuous sinks for O3, NO2 and PM2.5. All supply (mechanical ventilation) was removed, while return (exhaust fans) were maintained. Each room is considered a zone. Each leak is on the surface of either a wall, floor, or ceiling and represents cracks in the material or edges of windows and doors that may allow for airflow. The red arrow is pointing to the occupant, and the blue arrow is pointing to the window that is opened or closed. These were both moved to the living room during the smoking simulations.

2.2.3. Varied Parameters

Using previous methods used by the CONTAM studies mentioned in the introduction, currently available literature, and public databases, key information was extracted for relevant input parameters in the CONTAM model. Indoor source type was split into either gas stovetop cooking, electric stovetop cooking, or cigarette smoking. The emission and removal/deposition rates used are provided in Tables 2 and 3. There was limited data available on the emission rates of electric stovetop cooking when directly compared to gas stovetop cooking. A review study (Hu et al., 2012) compiled emission rates of various indoor sources and calculated emission rates of electric stovetops by using pollutant concentration and cooking time data from Zhang et al., 2008. Zhang et al. found there to be an estimated factor of 2 higher $PM_{2.5}$ concentrations from gas vs. electric stovetop cooking. Therefore, the gas stovetop emission rate (1.56 mg/min) was divided by 2 to represent electric stovetop emissions. The limitations of this estimate are discussed in the discussion section. It is important to note that other sources of pollution such as candle burning and cleaning can also lead to elevated indoor levels of pollution. However, these were omitted for the sake of time and due to the nature of the activities being less avoidable when compared to cooking and smoking. The cooking duration was split into 15-minute and 1-hour time periods, combining those used by Modera et al., 2022 and Underhill et al., 2020. Kitchen exhaust fans were either turned on for the duration of the cooking period plus an additional 30 minutes or off. For the smoking scenarios, two cigarettes were smoked within the first hour for 10 minutes, at the 18:00 and 18:30 time stamps. Outdoor air quality was either at Moderate or Unhealthy for Sensitive Groups (USG), as defined by the Air Quality Index (AQI) (US EPA). The middle values of each range were used. This corresponds to Moderate outdoor $PM_{2.5}$ levels of 24 $\mu g/m^3$ and USG outdoor $PM_{2.5}$ levels of 45.5 $\mu g/m^3$. For NO_2, outdoor levels were set at either 77 $\mu g/m^3$ (41 ppb) for Moderate AQI or 230 $\mu g/m^3$ (122 ppb) for USG AQI (Table S4). The window was either always closed, always open, or open temporarily. A strategic ventilation intervention for the temporarily opened window was chosen to be for the duration of the cooking time period plus an additional 30 minutes. This allowed for a comparison between the exhaust-only and strategic ventilation interventions.

Table 2: Variable Indoor Source Emission and Removal Rates

Source Type	**Indoor Emission Rate (mg/min)**	**Indoor Removal Rate (1/h)**	**Sources**
Gas Stovetop Cooking	**$PM_{2.5}$:** 1.56 **NO_2:** 1.1	**$PM_{2.5}$:** 0.19 **NO_2:** 0.86	Long et al., 2001; Dimitroulopoulou et al., 2006; Singer et al., 2009; Emmerich, 2005.
Electric Stovetop Cooking	**$PM_{2.5}$:** 0.78 **NO_2:** N/A	**$PM_{2.5}$:** 0.19 **NO_2:** 0.86	Hu et al., 2012; Zhang et al., 2010; Emmerich, 2005
Cigarette Smoking	**$PM_{2.5}$:** 1* **NO_2:** N/A *(10mg/cig*1cig/10min)	**$PM_{2.5}$:** 0.1 **NO_2:** 0.86	Underhill et al., 2020; Klepeis et al., 2017; Klepeis and Nazaroff, 2006.

Table 3: Continuous Source Ambient Concentrations, Emission and Removal Rates

Source Type	**Ambient Concentrations**	**Indoor Emission Rate (mg/min)**	**Indoor Removal Rate (1/h)**	**Sources**
Occupant (1)	**CO_2:** 400 ppm	**CO_2:** 0.0052 L/s	N/A	Persily and de Jonge, 2017
Moderate Ambient Air	**$PM_{2.5}$:** 24 $\mu g/m^3$ **NO_2:** 77 $\mu g/m^3$ **O_3:** 0.00625 ppm	N/A	**$PM_{2.5}$:** 0.19 **NO_2:** 0.86 **O_3:** 2.8	US EPA; Lee et al., 2011
USG Ambient Air	**$PM_{2.5}$:** 45.5 $\mu g/m^3$ **NO_2:** 230 $\mu g/m^3$ **O_3:** 0.0078 ppm	N/A	**$PM_{2.5}$:** 0.19 **NO_2:** 0.86 **O_3:** 2.8	US EPA; Lee et al., 2011

3. Results

3.1. Literature Review on Ventilation Options and Indoor Air Quality

The current literature was reviewed, and key information extracted to create guidelines on maintaining optimal indoor air quality through window-opening behavior. This information was translated into a flow chart with various potential real-world California residential scenarios (Figure 2). The summary of the literature review, and which the flow chart was based on, was categorized into four pollution scenarios: no indoor combustion with Good AQI, no indoor combustion with Poor AQI, indoor sources of combustion with Good AQI, and both indoor sources of combustion with Poor AQI. Poor AQI is defined in this study as an AQI category of Moderate or worse. Indoor source control along with air purifiers are additionally recommended under any scenario with outdoor or indoor sources of pollution. However, this study focused on ventilation, so it was not included as a primary intervention strategy, but rather a supplemental one in the results.

The results were used to create a preliminary flow chart to use to maintain optimal indoor air quality. Guidelines provide multiple potential intervention options to provide flexibility for an individual’s situation and available resources. These included mechanical ventilation with or without a filter, exhaust-only ventilation, and natural ventilation. Available guidelines and research provided intervention strategies for all situations except those that are more complex and resource-limited, as mentioned previously. These situations were instead informed by the CONTAM simulations (Figure 3).

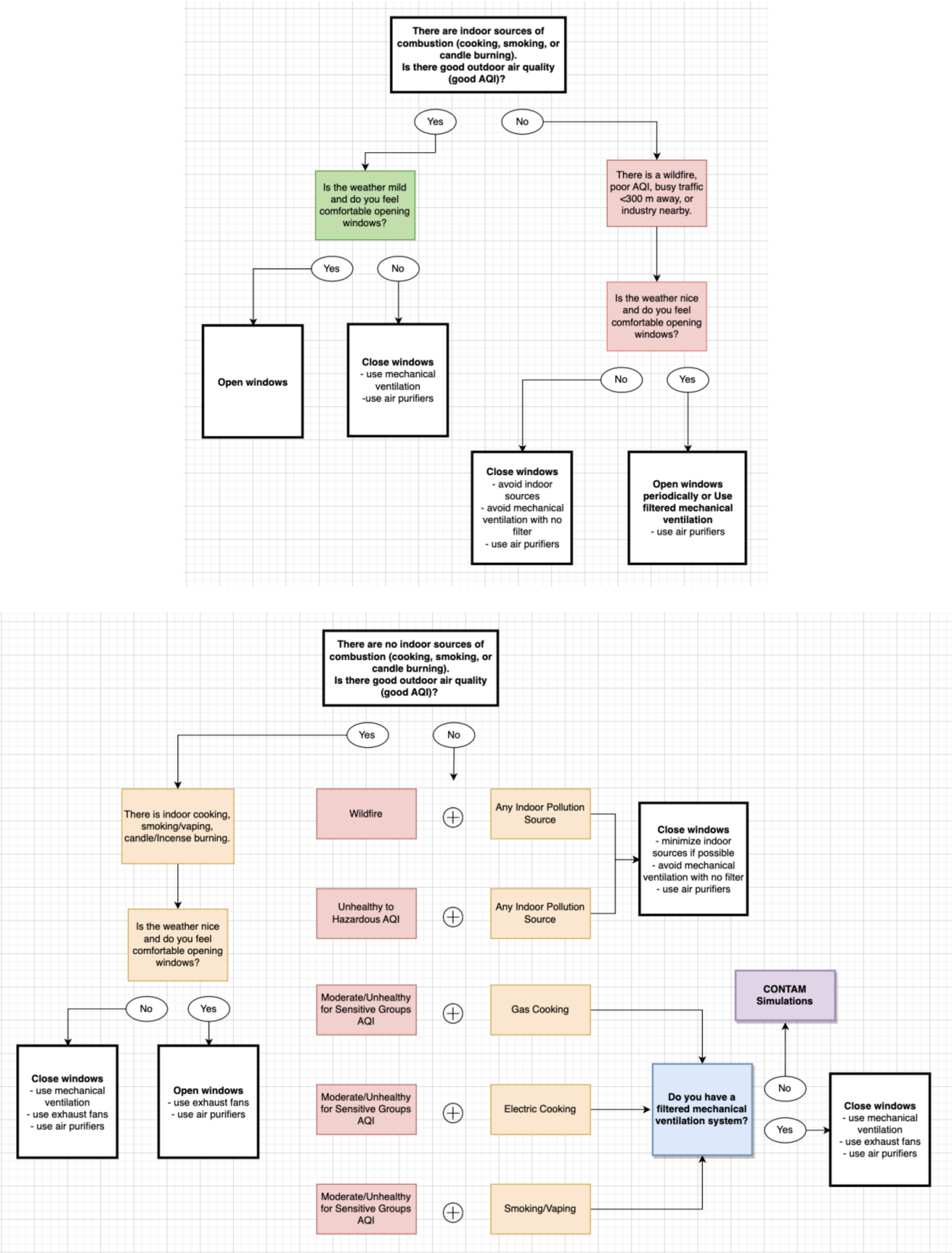


Figure 2: Flow Chart of Literature-Based Ventilation Guidelines

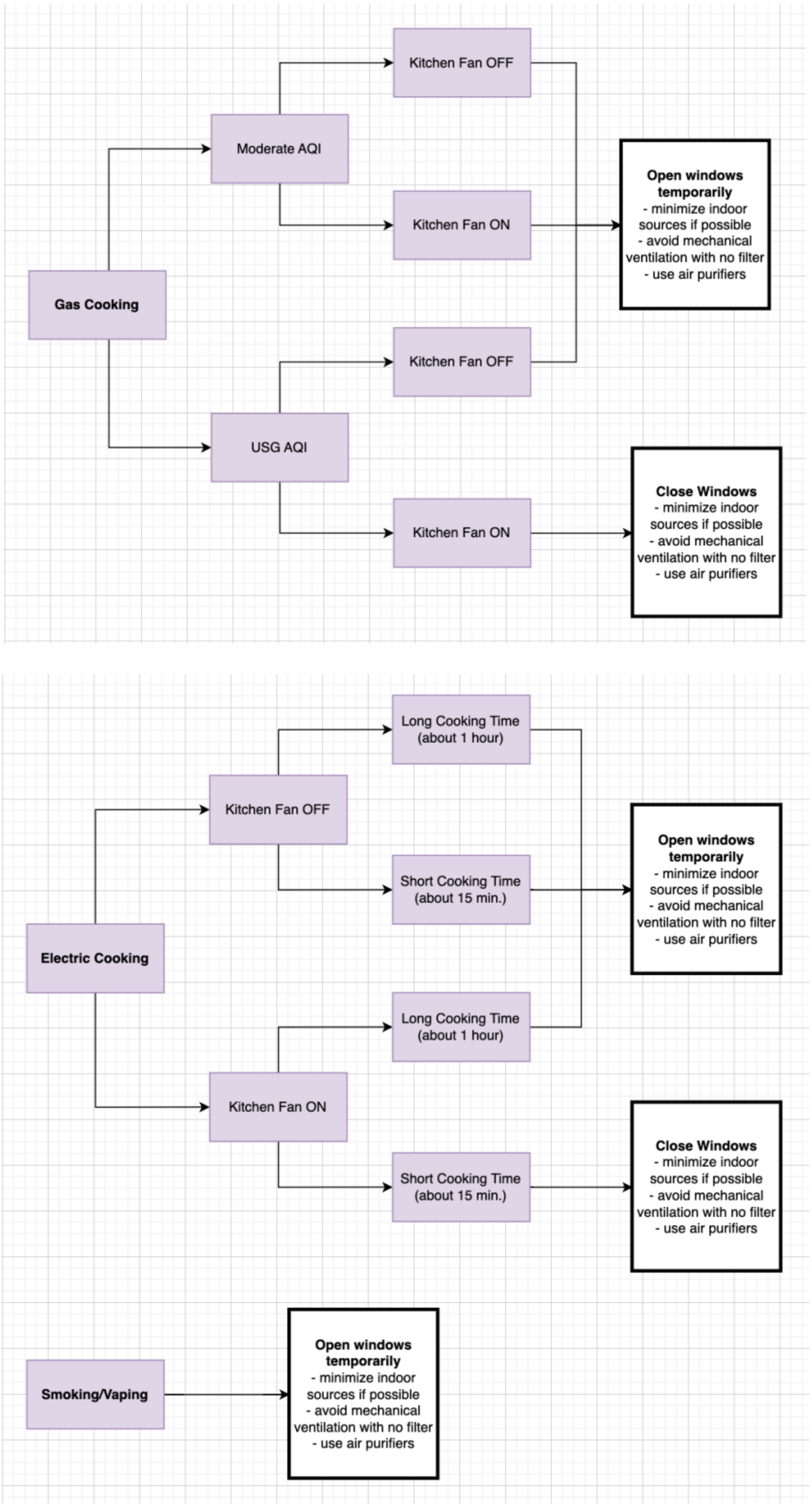


Figure 3: Flow Chart of CONTAM-Based Ventilation Guidelines

3.1.1. No Indoor Combustion Sources and Good AQI

In an ideal situation, in which there are no significant sources of indoor or outdoor pollution, it is still advised to operate a ventilation strategy that brings outdoor air in, as high levels of indoor pollutants and CO_2 can accumulate from indoor materials and occupants, leading to sick building syndrome (Joshi, 2008). Even if there are no high-emission sources like cooking or smoking, there are constant, lower-emission indoor residential sources of pollutants including building materials, earth radon, furnishings and household products, insulation, and moist materials. Therefore, pollutants that pose the highest concern for indoor occupant exposure in a tightly sealed envelope with minimal ventilation include formaldehyde, VOCs, and radon (Tham, 2016). Exposure to environmental tobacco smoke and radon decay products are impacted by ventilation rates (ECA, 2003). Gas stoves are also known to leak benzene, a known carcinogen, even when turned off (Lebel et al., 2022). This contributes to concerns surrounding building weatherization and retrofitting to create a tighter building envelope, as this can result in higher levels of indoor pollutants despite a decrease in the infiltration of outdoor pollutants and increased energy efficiency (Shrestha et al., 2019).

3.1.2. No Indoor Combustion Sources and Poor AQI

During wildfires, personal interventions relating to ventilation can include closing windows and doors and air filtration via a mechanical ventilation system or air purifier (Laumbach, 2019). Although filtered mechanical ventilation can filter outdoor air, it greatly depends on the efficiency of the filtration system (Kelly and Fussel, 2019). Shrestha et al., 2019 found that outdoor air pollution was brought indoors through mechanical ventilation and inadequately filtered out. The research was conducted in low-income households, where the mechanical ventilation systems were equipped with low-efficiency filters that were primarily intended to safeguard the equipment rather than deliver clean air to the conditioned area.

However, they found that only using exhaust fans in homes led to reduced indoor pollutant exposure.

When local AQI is unhealthy, recommended interventions are similar to those during wildfires. Natural and mechanical ventilation both have pros and cons and should be carefully implemented to reduce exposure levels (Laumbach et al., 2015). When indoor sources are effectively controlled, avoiding natural and mechanical ventilation is optimal for short periods of time when outdoor levels are excessively high. Residences situated near major roads and highways are at a heightened risk of increased infiltration of ultrafine particulate matter, leading to significant public health concerns. For new housing developments built in proximity to highways, ventilation strategies aim to reduce the infiltration of traffic-related particulate matter indoors. This can be achieved by positioning ventilation air intakes on the sides of buildings that face away from the highways and utilizing filtration (Shrestha et al., 2019; Tong et al., 2016). This is also true for residences near industrial processes, such as oil and gas drilling. A study conducted in California found that $PM_{2.5}$ and carbon monoxide levels were higher within 3 km of preproduction wells, NO_2 levels were elevated within 1-2 km, and ozone (O_3) levels were higher within 2-4 km from the wells (Gonzalez et al., 2022). This is especially a concern during flares associated with oil and gas extraction (Johnston et al., 2020), which can lead to high levels of ambient air pollution within 5 km of the pollution source. Therefore, residents nearby oil and gas industrial facilities should strategically implement natural ventilation by opening windows that face away from the pollution source such as a major road or refinery, while closing windows on the side facing the source (Tong et al., 2016). Overall, effective strategies for unhealthy outdoor air quality include indoor source behavior modifications, avoiding natural ventilation, and ensuring one’s mechanical ventilation system has an effective and well-maintained filter when in use.

3.1.3. Indoor Combustion Sources and Good AQI

In addition to the constant, lower-emission sources previously discussed, there are a variety of relatively high-emission indoor sources that occur at periodic time intervals, depending on individual occupant behavior. These include cooking, smoking, burning candles or incense, and cleaning (Klepeis et al., 2017; Hu et al., 2012; Knibbs et al., 2012). It is advised to always use available kitchen exhaust fans while cooking (Fabian et al., 2012). Exhaust fans, such as those in the bathroom, can also be used when using household cleaning products with volatile chemicals (ASHRAE; CDC). Depending on an individual's preference, it is also advised to either employ mechanical or natural ventilation (CDC; ASHRAE; Zhao et al., 2020; Li et al., 2017). Natural ventilation is preferred in situations with good ambient air quality, as it is more cost-effective, energy-efficient, and accessible when compared to mechanical ventilation. However, mechanical ventilation (supply-only, exhaust-only, and/or balanced) is preferred in situations in which there are safety concerns with keeping windows open or maintaining thermal comfort when outdoor temperatures are not mild. Air purifiers are also recommended as a supplemental intervention (US EPA; ASHRAE; CDC).

3.1.4. Indoor Combustion Sources and Poor AQI

Situations in which there are elevated levels of indoor and outdoor pollutants can make residential ventilation decision-making a complex and difficult task. For indoor sources, cooking and smoking are high-emission ones that are also more difficult to implement source control as people may rely on cooking appliances for food, and smoking behavior is difficult to change (Shrestha et al., 2019; Seppanen, 2016). Cooking is one of the most common of all indoor sources and has the potential to release significant levels of pollution. However, it also has a large range of emission rates and pollutant composition, depending on factors such as fuel type (gas or electric), cooking method (frying, grilling, baking, steaming, microwaving, etc.), oil type, and food type (Hu et al., 2012). For example, microwaving, which is associated with much lower emissions, can be a more ideal option over gas stovetop or oven use, especially when outdoor pollution levels are elevated. Exhaust fans are recommended during all cooking activities. Exhaust fans' pollutant capture efficiency can range from <15% to >98% but varies based on proper maintenance, burner position, and fan settings or features (Delp and Singer, 2012). All-electric buildings with electric cooking appliances do not have significant indoor sources of NO_2 emissions. However, the operation of kitchen exhaust fans is still recommended as food releases PM (Modera et al., 2022).

Typically, strategies are grouped and prioritized based on effectiveness in reducing indoor pollutant exposure (Levasseur et al., 2017). The US EPA recommends source control as a primary intervention, then improved ventilation, and air cleaners last. Source control involves behavior modifications like avoiding indoor smoking, reducing the use of gas stoves, candles/incense, and alternative cleaning methods. These are strategies that are cost-effective and easily accessible. The next group of interventions involves modifying ventilation, such as improving local exhaust ventilation in kitchens and employing natural and/or mechanical ventilation.   The third strategy involves air filtration/purification practices. Effective mechanical ventilation systems and air purifiers tend to be more costly and therefore less accessible to low-income households (Tsoulou et al., 2021; Seppanen, 2016). Therefore, they may require different ventilation strategies, depending on an individual's unique situation.

For those with mechanical ventilation, ventilation strategy largely relies on the efficiency and type of mechanical ventilation system in place. It's important for mechanical ventilation systems to have high filtration efficiency in order to successfully reduce exposure to $PM_{2.5}$ (Yuan et al., 2015). A study of 23 low-income apartments found they had measured airflows substantially below specification values. Therefore, efforts should be made to ensure properly functioning systems. Unit or household size also plays a role, as higher NO_2 was found in apartments compared to houses with similar cooking frequencies (Zhao et al., 2020). Therefore, exhaust fans are especially important in these settings. The highest indoor/outdoor ratios were observed in homes lacking kitchen stove hoods, followed by homes that had recirculating stove hoods, as compared to those equipped with exhaust-type stove hoods (Shrestha et al., 2019). As previously mentioned, facing ventilation air intakes on the sides of the buildings away from the outdoor pollution source and utilizing filtration are effective strategies.

Even in households with mechanical ventilation as an option, residents would benefit by prioritizing natural ventilation and using mechanical ventilation as needed, also known as hybrid ventilation. This ventilation strategy can reduce building energy consumption and costs without sacrificing indoor air quality. However, the effectiveness of this strategy largely depends on the local climate (Liu et al., 2021). To compare ventilation strategies in instances with both elevated indoor and outdoor levels of pollution, natural ventilation was found to be the cheapest, but it may provide an insufficient ventilation rate for 27%–79% of the occupied time. However, it is recommended for residential buildings with maximum potential to use it. Mechanical ventilation can ensure good indoor air quality continuously but can cost twice as much (Liu et al., 2021).

Source control is especially stressed for those who must rely on natural ventilation. Natural ventilation can effectively improve thermal comfort and indoor air quality in mild climates but isn’t practical in hot and humid climates or in cold climates. However, sometimes it is the only option. Ventilation openings should be strategically arranged and controlled to achieve desired airflow, but relying on them alone may not guarantee optimal temperature, humidity, and air quality due to wind and stack effects (ASHRAE 2001 Handbook). ASHRAE guidelines for natural ventilation recommend positioning windows in opposing pressure zones to increase ventilation flow. Placing two openings on opposite sides of a space provides greater ventilation flow, while openings on adjacent sides force air to change direction, thereby ventilating a larger area. Similar to mechanical ventilation inlets, windows on walls facing a major pollution source should remain closed while those on the opposite side should be prioritized for opening. Natural ventilation is unstable and not fully controllable and may sometimes be insufficient for reducing indoor contaminants. Therefore, indoor particle filtration through air purifiers or mechanical ventilation may be necessary (Liu et al., 2021).

One study compared using air purifiers paired with either natural ventilation or mechanical ventilation for reducing human exposure to indoor air pollutants. It was found that mechanical ventilation with an air purifier can more reliably reduce indoor pollutant exposure, while natural ventilation with air purifiers is better for those who require strategies with low cost and energy consumption (Ye et al., 2017). Other potential strategies like installing cooling devices to keep windows closed during pollution episodes in addition to using air cleaners on highly polluted days can reduce exposure to outdoor air pollution in low-income homes. Smart, low-cost sensor technologies can also offer greater control over residential ventilation. These measures collectively help minimize the health risks of outdoor air pollution for vulnerable low-income communities (Shrestha et al., 2019; Connolly et al., 2022).

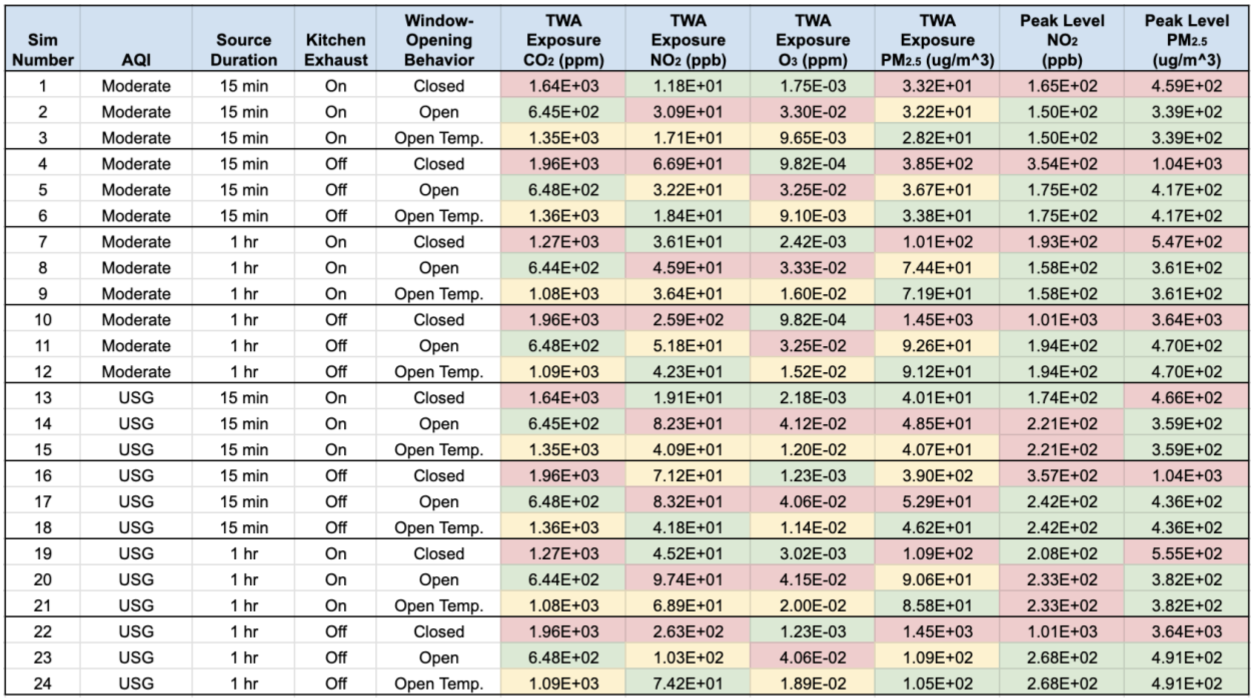
Overall, it can be deduced that during unhealthy or very unhealthy AQI, it’s best to avoid natural ventilation and mechanical ventilation without a high-efficiency filter altogether and take extra care to reduce indoor sources and use air purifiers. However, when the AQI is moderate or unhealthy for sensitive groups, and one is cooking indoors, the best strategy largely depends on various factors. If one is able, exhaust fans paired with filtered mechanical ventilation are a good option, along with air purifiers if needed. However, if natural ventilation is the only option, the right decision can change based on many situational factors. This is investigated in the next section.

3.2. CONTAM Simulation Scenarios

First, gas cooking was investigated (Table 4 and Figure 4). Results show that when cooking with a gas stove, keeping the window open at all times was never the best intervention for mitigating time-weighted average exposure to pollutants. However, choosing between keeping the window closed and opening the window temporarily depended on the situation.

Time-weighted average exposure to $PM_{2.5}$ was the lowest when the window was open temporarily under Moderate AQI. However, when AQI was Unhealthy for Sensitive Groups, this was the case for all scenarios except where there was a shorter cooking period and the kitchen exhaust fan was in use. In this case, keeping the window closed was better. For time-weighted average exposure to NO_2, the best strategy depended on kitchen fan use. In both Moderate/USG AQI and short/long cooking periods, keeping the window closed was best when the kitchen exhaust fan was on, while opening the window temporarily kept exposure at the lowest levels when the kitchen exhaust fan was off. When looking at peak levels of each pollutant, however, simply opening the window at some point (either for the entire time period or only temporarily) was key to reducing the maximum concentrations during a one-minute time interval under Moderate AQI conditions. This was not the case, however, for peak NO_2 levels under situations with USG AQI and the kitchen exhaust fan in use.

Table 4: Summary table of CONTAM simulation results for gas cooking scenarios. Each simulation was run with one of three natural ventilation interventions: closed window, open window, and open temporarily (strategic ventilation). Time-weighted average of the exposure was determined by calculating the area under the curve for occupant exposure levels at 1-minute time intervals from the time period of 18:00-24:00 on Day 4 in CONTAM, and then dividing by 360 minutes. Peak levels are the maximum occupant exposure levels at a 1-minute time interval from the time period of 18:00-24:00 in CONTAM. Green highlight indicates the lowest time-weighted average exposure, yellow indicates intermediate, and red indicates the highest time-weighted average exposure to the pollutant within each scenario. Abbreviations: AQI, air quality index; USG, unhealthy for sensitive groups; TWA, time-weighted average.



Sim Number	AQI	Source Duration	Kitchen Exhaust	Window-Opening Behavior	TWA Exposure CO_2 (ppm)	TWA Exposure NO_2 (ppb)	TWA Exposure O_3 (ppm)	TWA Exposure $PM_{2.5}$ (ug/m^3)	Peak Level NO_2 (ppb)	Peak Level $PM_{2.5}$ (ug/m^3)
1	Moderate	15 min	On	Closed	1.64E+03	1.18E+01	1.75E-03	3.32E+01	1.65E+02	4.59E+02
2	Moderate	15 min	On	Open	6.45E+02	3.09E+01	3.30E-02	3.22E+01	1.50E+02	3.39E+02
3	Moderate	15 min	On	Open Temp.	1.35E+03	1.71E+01	9.65E-03	2.82E+01	1.50E+02	3.39E+02
4	Moderate	15 min	Off	Closed	1.96E+03	6.69E+01	9.82E-04	3.85E+02	3.54E+02	1.04E+03
5	Moderate	15 min	Off	Open	6.48E+02	3.22E+01	3.25E-02	3.67E+01	1.75E+02	4.17E+02
6	Moderate	15 min	Off	Open Temp.	1.36E+03	1.84E+01	9.10E-03	3.38E+01	1.75E+02	4.17E+02
7	Moderate	1 hr	On	Closed	1.27E+03	3.61E+01	2.42E-03	1.01E+02	1.93E+02	5.47E+02
8	Moderate	1 hr	On	Open	6.44E+02	4.59E+01	3.33E-02	7.44E+01	1.58E+02	3.61E+02
9	Moderate	1 hr	On	Open Temp.	1.08E+03	3.64E+01	1.60E-02	7.19E+01	1.58E+02	3.61E+02
10	Moderate	1 hr	Off	Closed	1.96E+03	2.59E+02	9.82E-04	1.45E+03	1.01E+03	3.64E+03
11	Moderate	1 hr	Off	Open	6.48E+02	5.18E+01	3.25E-02	9.26E+01	1.94E+02	4.70E+02
12	Moderate	1 hr	Off	Open Temp.	1.09E+03	4.23E+01	1.52E-02	9.12E+01	1.94E+02	4.70E+02
13	USG	15 min	On	Closed	1.64E+03	1.91E+01	2.18E-03	4.01E+01	1.74E+02	4.66E+02
14	USG	15 min	On	Open	6.45E+02	8.23E+01	4.12E-02	4.85E+01	2.21E+02	3.59E+02
15	USG	15 min	On	Open Temp.	1.35E+03	4.09E+01	1.20E-02	4.07E+01	2.21E+02	3.59E+02
16	USG	15 min	Off	Closed	1.96E+03	7.12E+01	1.23E-03	3.90E+02	3.57E+02	1.04E+03
17	USG	15 min	Off	Open	6.48E+02	8.32E+01	4.06E-02	5.29E+01	2.42E+02	4.36E+02
18	USG	15 min	Off	Open Temp.	1.36E+03	4.18E+01	1.14E-02	4.62E+01	2.42E+02	4.36E+02
19	USG	1 hr	On	Closed	1.27E+03	4.52E+01	3.02E-03	1.09E+02	2.08E+02	5.55E+02
20	USG	1 hr	On	Open	6.44E+02	9.74E+01	4.15E-02	9.06E+01	2.33E+02	3.82E+02
21	USG	1 hr	On	Open Temp.	1.08E+03	6.89E+01	2.00E-02	8.58E+01	2.33E+02	3.82E+02
22	USG	1 hr	Off	Closed	1.96E+03	2.63E+02	1.23E-03	1.45E+03	1.01E+03	3.64E+03
23	USG	1 hr	Off	Open	6.48E+02	1.03E+02	4.06E-02	1.09E+02	2.68E+02	4.91E+02
24	USG	1 hr	Off	Open Temp.	1.09E+03	7.42E+01	1.89E-02	1.05E+02	2.68E+02	4.91E+02

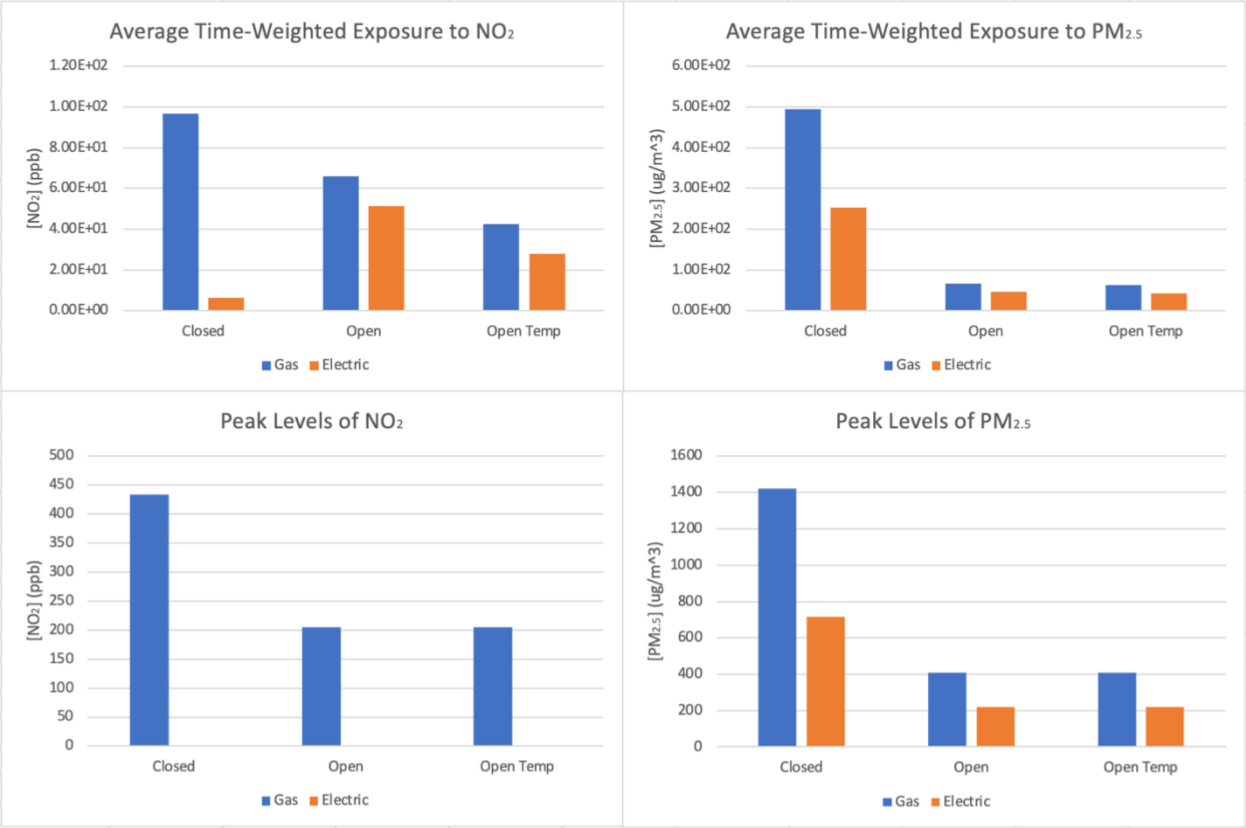
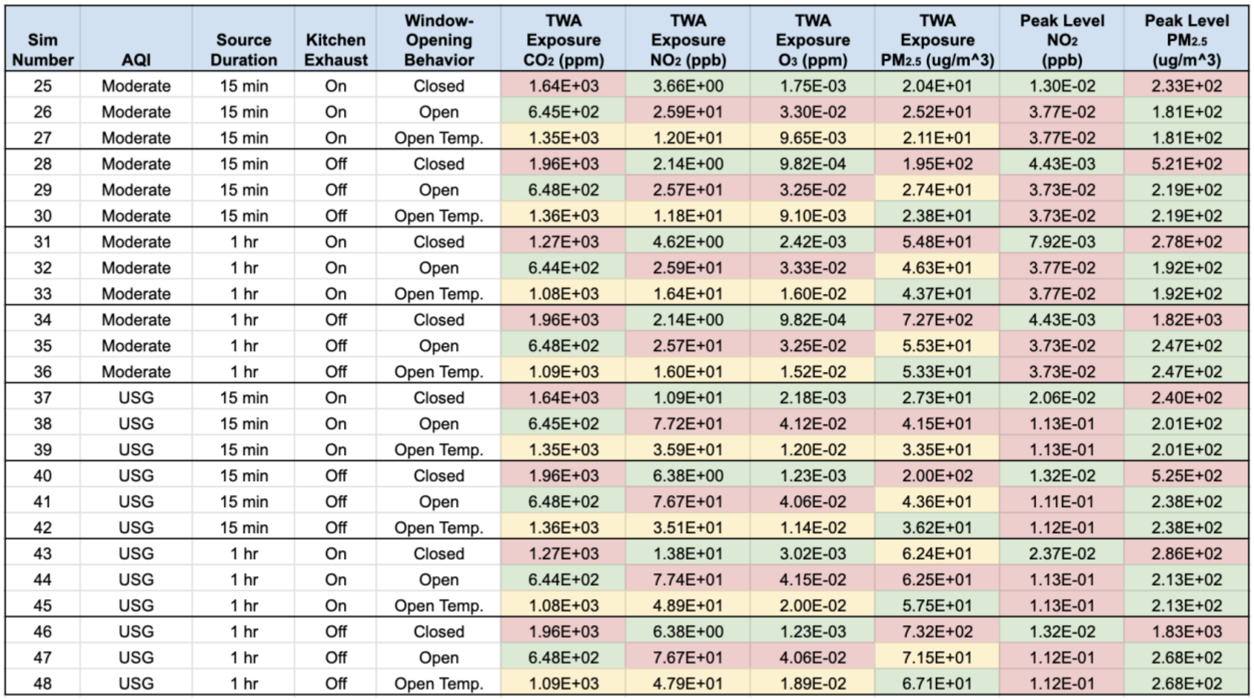


Figure 4: Time-weighted averages and peak levels of exposure to NO_2 and $PM_{2.5}$ averaged across all simulation scenarios to compare gas and electric cooking conditions.

Next, the simulations were run again, but with electric stovetop cooking (Table 5 and Figure 4). As seen with gas cooking, keeping the window open the entire time period was never the best option for reducing time-weighted average exposure to $PM_{2.5}$, and the optimal strategy depended on different factors. Under both moderate and USG AQI, opening the window temporarily was the best option except when the cooking time was short and the kitchen exhaust fan was on. Under this scenario, keeping the window closed was optimal. Keeping the window closed was optimal for NO_2 exposure levels. This is expected as electric cooking does not generate NO_2, which is also why the peak levels for this pollutant were not included in the summary table. As seen with gas cooking, opening the window at some point was key to reducing peak levels of the indoor-generated pollutant ($PM_{2.5}$).

Overall, the data for gas and electric cooking suggests that opening the window temporarily is the best option for mitigating both time-weighted average exposure and peak levels to $PM_{2.5}$ and NO_2 under elevated outdoor air pollution levels (Figure 4), except when one has a functioning exhaust fan in use and is only cooking for a short time period (about 15 minutes).

Table 5: Summary table of CONTAM simulation results for electric cooking scenarios. Each simulation was run with one of three natural ventilation interventions: closed window, open window, and open temporarily (strategic ventilation). Time-weighted average of the exposure was determined by calculating the area under the curve for occupant exposure levels at 1-minute time intervals from the time period of 18:00-24:00 on Day 4 in CONTAM, and then dividing by 360 minutes. Peak levels are the maximum occupant exposure levels at a 1-minute time interval from the time period of 18:00-24:00 in CONTAM. Green highlight indicates the lowest time-weighted average exposure, yellow indicates intermediate, and red indicates the highest time-weighted average exposure to the pollutant within each scenario. Abbreviations: AQI, air quality index; USG, unhealthy for sensitive groups; Temp., Temporarily; TWA, time-weighted average.



Sim Number	AQI	Source Duration	Kitchen Exhaust	Window-Opening Behavior	TWA Exposure CO_2 (ppm)	TWA Exposure NO_2 (ppb)	TWA Exposure O_3 (ppm)	TWA Exposure $PM_{2.5}$ (ug/m^3)	Peak Level NO_2 (ppb)	Peak Level $PM_{2.5}$ (ug/m^3)
25	Moderate	15 min	On	Closed	1.64E+03	3.66E+00	1.75E-03	2.04E+01	1.30E-02	2.33E+02
26	Moderate	15 min	On	Open	6.45E+02	2.59E+01	3.30E-02	2.52E+01	3.77E-02	1.81E+02
27	Moderate	15 min	On	Open Temp.	1.35E+03	1.20E+01	9.65E-03	2.11E+01	3.77E-02	1.81E+02
28	Moderate	15 min	Off	Closed	1.96E+03	2.14E+00	9.82E-04	1.95E+02	4.43E-03	5.21E+02
29	Moderate	15 min	Off	Open	6.48E+02	2.57E+01	3.25E-02	2.74E+01	3.73E-02	2.19E+02
30	Moderate	15 min	Off	Open Temp.	1.36E+03	1.18E+01	9.10E-03	2.38E+01	3.73E-02	2.19E+02
31	Moderate	1 hr	On	Closed	1.27E+03	4.62E+00	2.42E-03	5.48E+01	7.92E-03	2.78E+02
32	Moderate	1 hr	On	Open	6.44E+02	2.59E+01	3.33E-02	4.63E+01	3.77E-02	1.92E+02
33	Moderate	1 hr	On	Open Temp.	1.08E+03	1.64E+01	1.60E-02	4.37E+01	3.77E-02	1.92E+02
34	Moderate	1 hr	Off	Closed	1.96E+03	2.14E+00	9.82E-04	7.27E+02	4.43E-03	1.82E+03
35	Moderate	1 hr	Off	Open	6.48E+02	2.57E+01	3.25E-02	5.53E+01	3.73E-02	2.47E+02
36	Moderate	1 hr	Off	Open Temp.	1.09E+03	1.60E+01	1.52E-02	5.33E+01	3.73E-02	2.47E+02
37	USG	15 min	On	Closed	1.64E+03	1.09E+01	2.18E-03	2.73E+01	2.06E-02	2.40E+02
38	USG	15 min	On	Open	6.45E+02	7.72E+01	4.12E-02	4.15E+01	1.13E-01	2.01E+02
39	USG	15 min	On	Open Temp.	1.35E+03	3.59E+01	1.20E-02	3.35E+01	1.13E-01	2.01E+02
40	USG	15 min	Off	Closed	1.96E+03	6.38E+00	1.23E-03	2.00E+02	1.32E-02	5.25E+02
41	USG	15 min	Off	Open	6.48E+02	7.67E+01	4.06E-02	4.36E+01	1.11E-01	2.38E+02
42	USG	15 min	Off	Open Temp.	1.36E+03	3.51E+01	1.14E-02	3.62E+01	1.12E-01	2.38E+02
43	USG	1 hr	On	Closed	1.27E+03	1.38E+01	3.02E-03	6.24E+01	2.37E-02	2.86E+02
44	USG	1 hr	On	Open	6.44E+02	7.74E+01	4.15E-02	6.25E+01	1.13E-01	2.13E+02
45	USG	1 hr	On	Open Temp.	1.08E+03	4.89E+01	2.00E-02	5.75E+01	1.13E-01	2.13E+02
46	USG	1 hr	Off	Closed	1.96E+03	6.38E+00	1.23E-03	7.32E+02	1.32E-02	1.83E+03
47	USG	1 hr	Off	Open	6.48E+02	7.67E+01	4.06E-02	7.15E+01	1.12E-01	2.68E+02
48	USG	1 hr	Off	Open Temp.	1.09E+03	4.79E+01	1.89E-02	6.71E+01	1.12E-01	2.68E+02

Finally, cigarette smoking (2 cigarettes/hour) was investigated. Results were the same under the two different AQI scenarios (Table 6). Time-weighted average exposure to $PM_{2.5}$ was greatest during the closed window strategy, in the middle during strategic ventilation, and lowest with the open window. Indoor CO_2 showed similar results. However, as expected, the outdoor-sourced pollutants (NO_2 and O_3 in this situation) showed flipped results. Strategic ventilation provided time-weighted average exposure to all pollutants in the middle. This strategy also kept peak $PM_{2.5}$ levels lower. As seen before, opening the window led to similar peak concentrations as opening temporarily, while keeping the window closed led to the highest peak concentrations of the indoor-sourced pollutant. Therefore, strategic ventilation (opening the window temporarily) is optimal for reducing both time-weighted average and peak pollutant exposures to an indoor occupant.

Table 6: Summary table of CONTAM simulation results for cigarette smoking scenarios. Each simulation was run with one of three natural ventilation interventions: closed window, open window, and window open temporarily (strategic ventilation). Time-weighted average of the exposure was determined by calculating the area under the curve for occupant exposure levels at 1-minute time intervals from the time period of 18:00-24:00 on Day 4 in CONTAM, and then dividing by 360 minutes. Peak levels are the maximum occupant exposure levels at a 1-minute time interval from the time period of 18:00-24:00 in CONTAM. Green highlight indicates the lowest time-weighted average exposure, yellow indicates intermediate, and red indicates the highest time-weighted average exposure to the pollutant within each scenario. Abbreviations: AQI, air quality index; USG, unhealthy for sensitive groups; Temp., Temporarily; TWA, time-weighted average.

Sim Number	AQI	Source Duration	Kitchen Exhaust	Window-Opening Behavior	TWA Exposure CO_2 (ppm)	TWA Exposure NO_2 (ppb)	TWA Exposure O_3 (ppm)	TWA Exposure $PM_{2.5}$ (ug/m^3)	Peak Level NO_2 (ppb)	Peak Level $PM_{2.5}$ (ug/m^3)
49	Moderate	2 cig/hr	N/A	Closed	9.50E+02	3.81E+00	1.95E-03	1.26E+02	1.32E-02	2.76E+02
50	Moderate	2 cig/hr	N/A	Open	6.37E+02	2.12E+01	2.16E-02	3.40E+01	9.36E-02	1.51E+02
51	Moderate	2 cig/hr	N/A	Open Temp.	8.08E+02	1.15E+01	7.95E-03	4.60E+01	9.14E-02	1.51E+02
52	USG	2 cig/hr	N/A	Closed	9.50E+02	1.14E+01	2.43E-03	1.36E+02	4.43E-03	2.86E+02
53	USG	2 cig/hr	N/A	Open	6.37E+02	6.32E+01	2.69E-02	5.09E+01	3.13E-02	1.71E+02
54	USG	2 cig/hr	N/A	Open Temp.	8.08E+02	3.45E+01	9.92E-03	6.12E+01	3.07E-02	1.71E+02

CO_2 and O_3 were also considered under all scenarios to represent indoor-only and outdoor-only sources, respectively. As expected, CO_2 levels were lowest when the window was open, in the middle when the window was opened temporarily, and highest when the window was closed during the 6-hour period. Conversely, ozone levels were lowest when the window was closed, in the middle when the window was opened temporarily, and highest when the window were open (Figure 5).

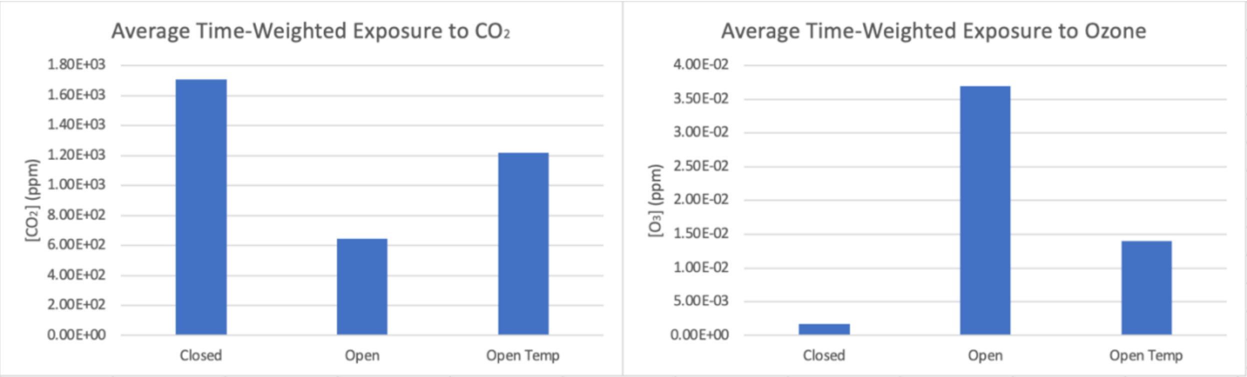


Figure 5: Average time-weighted exposure to CO_2 and Ozone, averaged over the three window-opening strategies (closed, open, and open temporarily).

4. Discussion

This study provides a comprehensive narrative review of current research-backed guidelines supplemented with modelled scenario testing to identify optimal ventilation procedures for California households. The review extracted key findings from currently available literature and official guidelines and translated them into a written summary and flow chart. Ventilation was the focus, with other strategies such as source control and air purification as complementary suggestions. There is a large and complex array of research to inform ventilation procedures, with uncertain evidence on the optimal choice under complex scenarios. The narrative review informed the more straightforward scenarios. In general, natural ventilation is optimal when environmental conditions like mild weather and secure conditions are present. However, filtered mechanical ventilation is an ideal alternative ventilation strategy to maintain optimal indoor air quality when environmental conditions prevent the use of natural ventilation. The flow chart provided in this paper is an accessible and straightforward tool for individuals to not only choose the best ventilation option for one's unique situation but to also better understand the factors that contribute to indoor air quality. It can be used for all California residential households, as it covers the full range of ventilation options. In addition, CONTAM allowed for a low-cost and accessible means of investigating relevant air quality research questions. The results provide focused and tailored recommendations in complex situations that involve both indoor and outdoor pollution sources and are resource limited. Results show that strategic ventilation, or opening windows for an efficient amount of time to achieve desired ventilation outcomes is optimal for reducing exposure to indoor pollutants under most scenarios, whereas closed windows may be a better option when cooking for short periods with an effective exhaust fan. This may be due to a reduction in the infiltration of outdoor air pollutants, an improvement in the effectiveness of the exhaust fan when windows are closed, or some other variable. Results are a bit more complex when only looking at time-weighted average exposure for significant indoor-sourced pollutants ($PM_{2.5}$ and NO_2) but follow the previous summary statement when accounting for both time-weighted average and peak concentration exposure to all pollutants.

There is difficulty in weighing the pros and cons of opening windows, as there are multiple pollutants to consider. For example, opening windows is usually associated with higher ozone exposure as it is a predominantly outdoor pollutant (Nazaroff and Weschler, 2021). However, this strategy is also associated with lower CO_2 levels, which only reach dangerous levels in indoor environments with low infiltration of fresh, outdoor air. This study demonstrated this by also investigating CO_2 and O_3 levels under each scenario. As expected, CO_2 levels were lowest when windows were open, in the middle when windows were opened temporarily, and highest when windows were closed. This was flipped with ozone concentrations. This provides additional benefit to opening windows temporarily, as they can maintain healthier levels of indoor CO_2, along with other indoor pollutants. The strategic ventilation strategy can also mitigate infiltration of outdoor ozone. This provides more weight towards the benefits of strategic ventilation, especially if there are vulnerable cohabitants (children, elderly, those with asthma or other respiratory issues). However, it is also worth noting that a behavior change, such as smoking outdoors, may be more effective than temporarily opening windows.

Peak exposure levels modelled in this study were in accordance with previous research. $PM_{2.5}$ peak concentrations have been previously found to reach 1366 μg/m^3 over a 2-minute interval (Huboyo et al., 2011). This study found similar average peak levels of about 1400 μg/m^3 for $PM_{2.5}$ under closed window conditions. For NO_2, field studies have found peak concentrations to reach levels of 1000 ppb (1880 μg/m^3), all the way up to about 1600 ppb (3000 μg/m^3), when cooking on gas stoves indoors (Dennekamp et al., 2001; Goldstein and Andrews, 1987). The 2022 report by Modera et al. found a maximum of about 190 ppb (360 μg/m^3) NO_2 at peak concentrations, with a maximum of 27 minutes of cooking. Under closed windows conditions, this study found average NO_2 levels to peak at around 434 ppb (816 μg/m^3), with the highest peak at 1010 ppb (1900 μg/m^3) for the simulation with gas cooking, windows closed and kitchen exhaust fan off. The large range in typical peak NO_2 concentrations is likely attributed to the large number of variables that have not been controlled for, such as cooking time, strength, type, window-opening behavior and building characteristics, to name a few. Peak concentrations of indoor air pollutants are important to consider as previous studies show a significant adverse effect of gas stove exposure on respiratory health in children, with increased risk associated with exposure to peak levels of NO_2 (Garrett et al., 1998; Kattan et al., 2007). Peak NO_2 exposure may be a critical factor in asthma exacerbation in children, further supporting the need for alternative methods of cooking, such as electric stoves. The adverse health effects may also be worse during the heating season, especially for low-income households due to decreased use of natural ventilation and use of gas stoves for heating (Zota et al., 2005). They also stress that the use of exhaust hoods should be prioritized, especially in households with asthmatic children. Results from this study also indicated that sometimes kitchen exhaust fans were more effective at reducing peak NO_2 levels than opening windows under USG AQI.

Results demonstrate that cooking stove type and cigarette smoking influence modelled concentrations and recommendations. Cigarette smoking showed that the optimal window-opening strategy was strategic ventilation, mostly due to the mitigation of exposure to $PM_{2.5}$ and moderate exposure to other pollutants. For the cooking situations, gas and electric had distinct results. Unlike gas stoves, indoor-generated NO_2 is not an issue associated with electric stoves, as they do not generate NO_2. Results also demonstrated significantly lower exposure to $PM_{2.5}$ when cooking with electric stoves, for both time-weighted average and peak concentrations. Therefore, this study highlights the importance of building electrification, not only for climate change mitigation but also to improve indoor air quality. Those with electric stoves and natural ventilation will be able to avoid excess exposure to outdoor pollutants as windows may need to be opened for much shorter periods of time to effectively reduce cooking-related pollutants. Replacement of gas stovetops with electric ones has been shown to be one of the most efficient measures for control of people's high exposure to pollutants from natural gas burners (Amirkhani Ardeh et al., 2020).

The CONTAM simulations in this study specifically looked at outdoor pollution levels at an AQI of moderate to unhealthy for sensitive group levels. These ambient levels are common across California and greatly impact indoor levels as well (Zhao et al., 2021). Low-income housing often exhibits higher dwelling permeability or leakage, which can impact indoor air quality maintenance. Household behavior plays a more crucial role in determining energy consumption and indoor air quality than household or unit size alone. Socioeconomic factors have significant implications for household behaviors and energy usage. These factors include occupants' varying needs based on age and health, domestic habits, consumption patterns, as well as indoor thermal preferences. Consequently, household behavior is a source of uncertainty that can greatly influence the accuracy of predictive models (Abdalla et al., 2021). The finding that building leakage in multi-family buildings can affect the inter-unit transfer of pollutants adds another potential pollution source besides outdoor and personal indoor emissions (Modera et al., 2022). Although closing windows may be less impactful in leakier homes, the results show that it is still optimal with significant indoor sources like gas cooking. In both hot and cold seasons, low socio-economic households experience higher concentrations of $PM_{2.5}$ indoors. This can be attributed to several factors, including elevated outdoor pollution levels, higher rates of indoor smoking, and buildings with fewer external facades for exchanging outdoor air. During the early morning hours, $PM_{2.5}$ concentrations are highest in both low socio-economic households and households above the low-income threshold. This is primarily due to increased infiltration of outdoor-sourced air pollution, as window opening increases air exchange rates when indoor sources are minimal. Throughout the day, emissions from indoor cooking and smoking activities contribute to higher $PM_{2.5}$ levels in both socioeconomic groups, particularly during the winter when window-opening frequencies decrease, resulting in lower air exchange rates (Ferguson et al., 2020). Overall, results for optimal window-opening strategy did change under both the moderate and USG AQI conditions. However, it was assumed that the point at which natural ventilation should be avoided entirely was under unhealthy or hazardous AQI. Future research may identify the exact tipping point. Future research should also include more simulations through the integration of more factors such as other pollutants, weather conditions, and other relevant building characteristics (window surface area, building materials, etc.).

It is important to discuss the limitations of this report. Despite its strengths, CONTAM is a model that cannot account for the intricacies of reality, and therefore will always be associated with levels of uncertainty. Also, due to the compounding nature of simulation scenarios when more variable factors are introduced, only four factors were investigated under two categories (AQI, cooking duration, exhaust fan use, and source type). However, there is a multitude of factors that could influence airflow within a residential building (indoor/outdoor temperature differences, wind speed, room height, window surface area, dwelling type, etc.). The temperature difference between indoor and outdoor environments creates a force called the "stack effect." In winter, warm indoor air rises and escapes through the roof, while cold outdoor air enters through the base. In summer, this process is reversed, with cold indoor air exiting through the base and hot outdoor air entering through the roof. In cold climates, the stack effect dominates airflow during the heating season. Buildings in temperate climates, like Los Angeles, experience less natural infiltration due to smaller pressure differentials caused by the stack effect and wind. Comparing Sacramento and Los Angeles, increasing leakage has a greater impact on the ventilation rate in Sacramento. In California, the average family's energy usage for heating and cooling is around 30%, lower than the national average of approximately 40%, mainly due to the state's mild climate. However, California has 16 different climate zones, each with unique heating and cooling needs (Modera et al., 2022). Openings near the neutral pressure level (NPL) have the least impact on thermally induced ventilation. When a building has a single large opening, the NPL tends to shift towards that level, resulting in reduced pressure across the opening (ASHRAE 2001 Handbook). Also, windows are more likely to be opened on comfortable days when the temperature difference between indoor and outdoor environments is small (Fabi et al., 2012). Consequently, the stack effect is less significant when windows are open, as thermal equilibrium is established between the indoor and outdoor temperatures, leading to a reduction in the stack effect (Breen et al., 2014). Therefore, stack effect-related factors were not considered in this study. Another limitation was only one type of building was used. It was an older, leakier, multi-family building and the occupant was assumed to stay inside all day on the second floor. Single-family buildings, manufactured homes, and attached buildings may have slightly different results. However, the multi-family building used was assumed to be the most representative of a situation in which a household would have limited resources and ventilation options, which is the situation that is the focus of the CONTAM simulations portion. This study also did not investigate all potential indoor pollutants, such as VOCs (including formaldehyde) and radon exposure, as these are predominantly indoor pollutants (Ye et al., 2017). Smoking simulations only looked at $PM_{2.5}$ emitted from cigarettes. However, it is also associated with a multitude of other toxic emissions, such as VOCs and benzene (McAuley et al., 2012; Protano et al., 2012). It is also important to note the knowledge gap regarding electric stove emission rates. Current field studies lack data directly comparing gas and electric stoves while holding other cooking factors constant. As previously mentioned, a review study (Hu et al., 2012) compiled emission rates of various indoor sources and cited an estimated factor of 2 higher $PM_{2.5}$ concentrations from gas vs. electric stovetop cooking. Therefore, in this study, the gas stovetop emission rate (1.56 mg/min) was divided by 2 to represent electric emissions. This estimate is highly uncertain due to the indirect nature of the calculation. It is also important to note the large range of cooking emission rates depending on cooking oil, food type, and cooking temperature (Hu et al., 2012). Therefore, indoor pollutant exposure results from this study could be overestimated if occupants used lower heat settings or underestimated if occupants used higher heat settings, for example. The mitigating effect of kitchen exhaust fans is also highly variable, which was not investigated in this study. Although the use of kitchen exhaust fans can help by capturing indoor pollutants, their typical capture efficiency is only around 60% for back burners and 25-30% for front burners (Delp and Singer, 2012). This efficiency also depends on proper use and cooking practices.

To reduce adverse health effects from tighter building envelopes that increase energy efficiency and reduce infiltration, California implemented new ventilation efficiency standards in 2008, known as Title 24. In newer or weatherized homes with tighter building envelopes, indoor air quality is still of concern as it can lead to the buildup of indoor pollutants. These new high-performance home standards and building codes mandate the use of mechanical ventilation systems to effectively manage indoor moisture and air pollutants. Available research highlights the effectiveness of this residential ventilation requirement implemented in California. One study wherein nearly all examined homes were equipped with compliant ventilation systems found the combination of mechanical ventilation and the implementation of a standard that limits formaldehyde emissions from manufactured wood products led to significantly lower formaldehyde concentrations in the newly constructed homes. On average, formaldehyde levels were reduced by 44% and 38% at mean and median levels, respectively, compared to homes built before the implementation of the standards (Singer et al., 2020). Another study involved 70 homes constructed between 2011 and 2017. Researchers monitored each home for approximately one week while the mechanical ventilation system was operational and windows were closed. The findings indicated that most homes met the ventilation requirements, with ventilation fans moving an average of 50% more air than the minimum specified in the Title 24 standards (Chan et al., 2020). These studies emphasize that new homes can adhere to stringent efficiency standards without compromising indoor air quality, although improvements are needed in terms of labeling and controls for ventilation systems.

Results of this report should be interpreted carefully and with consideration of confounding variables that may alter the recommendations. Although the results apply to many situations, real-life decision making depends on many factors. For example, individuals typically use natural ventilation for maintaining optimal thermal comfort, as opposed to reducing pollutant levels indoors (Fabi et al., 2012). Modera et al. summarized literature findings on typical window-opening behavior, reporting that windows tend to be open longest in summer, shortest in winter, and intermediate in autumn and spring. Wind speed also plays a role, as nearly all windows were found to be closed at wind speeds above 8 m/s (Modera et al., 2022). Residential air exchange rates tend to be higher in the metropolitan Los Angeles basin than in other areas of California (northern California and San Diego) and the United States, potentially due to higher use of natural ventilation in a relatively warm climate (Wilson et al. 1996). Another driver for the use of natural ventilation is the relative accessibility and cost of the intervention, as opening windows incurs no extra financial cost as compared with mechanical ventilation and air purifiers. Low-income households are more likely to resort to natural ventilation to save money, although other factors may contribute to window-opening behavior. For example, some may be less inclined to open windows due to safety concerns (Tsoulou et al., 2021). Therefore, it may be impractical to follow these recommendations given other factors that govern window-opening behavior such as thermal comfort, wind speed, and safety concerns.

5. Conclusion

The review provides guidelines for households to optimize residential indoor air quality under various situations to make more informed decisions on window-opening behavior and other ventilation options. For low-income residential buildings, strategic ventilation (temporarily opening windows during and until about 30 minutes after turning off the indoor source) has the potential to be a low-cost and accessible ventilation strategy to reduce exposure to indoor air pollutants when exhaust fans are broken or unavailable, and natural ventilation is the only available option. This report also supports the use of electric appliances, as they are associated with significantly lower indoor pollutants and overall reduced occupant exposure. They may provide low-income residences with more flexibility in ventilation options, like leaving windows closed when outdoor pollution is elevated. This report emphasizes the importance of utilizing exhaust fans while cooking, underscoring the need for well-maintained and efficient fans in low-income households.

6. Appendix: Supplementary Information

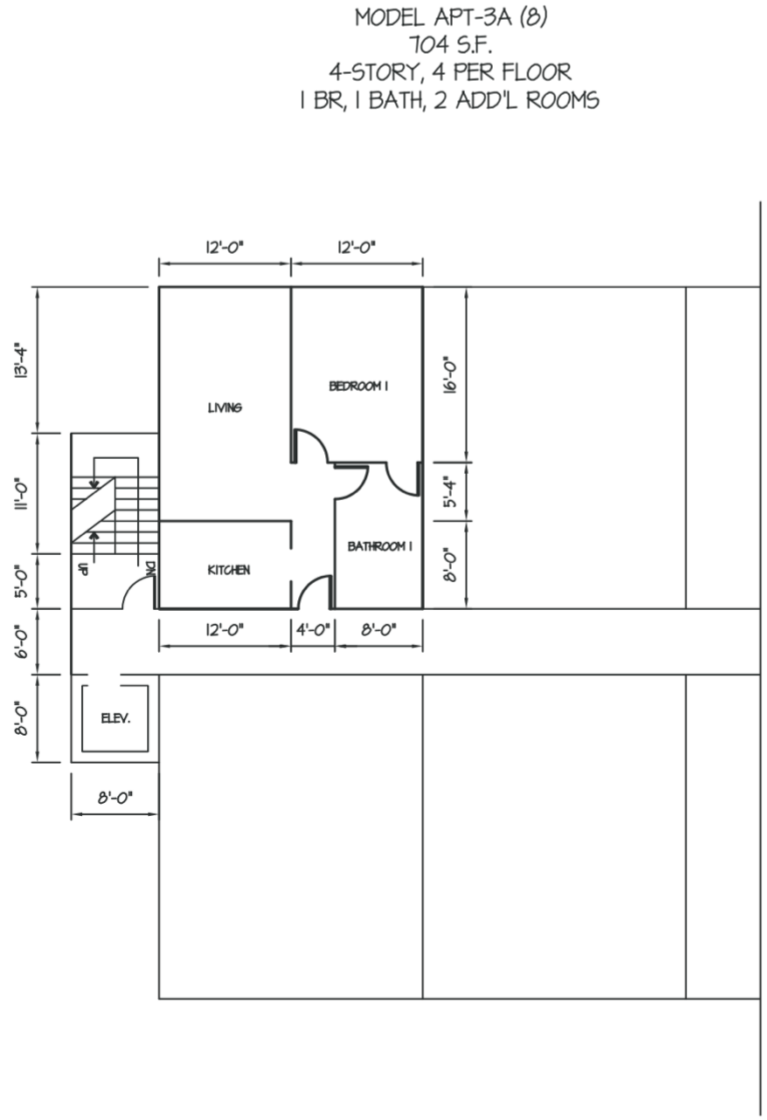
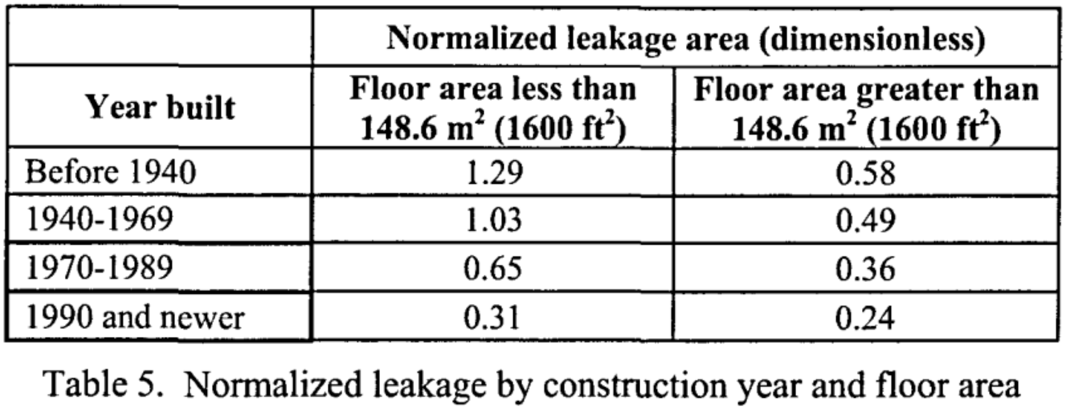


Figure S1: NIST Floor Plan of APT-26 (Case 11)

Table S1: Normalized Leakage by construction year and floor area from NIST (Persily et al., 2006).



	Normalized leakage area (dimensionless)	
Year built	**Floor area less than 148.6 m^2 (1600 ft^2)**	**Floor area greater than 148.6 m^2 (1600 ft^2)**
Before 1940	1.29	0.58
1940-1969	1.03	0.49
1970-1989	0.65	0.36
1990 and newer	0.31	0.24

Table 5. Normalized leakage by construction year and floor area

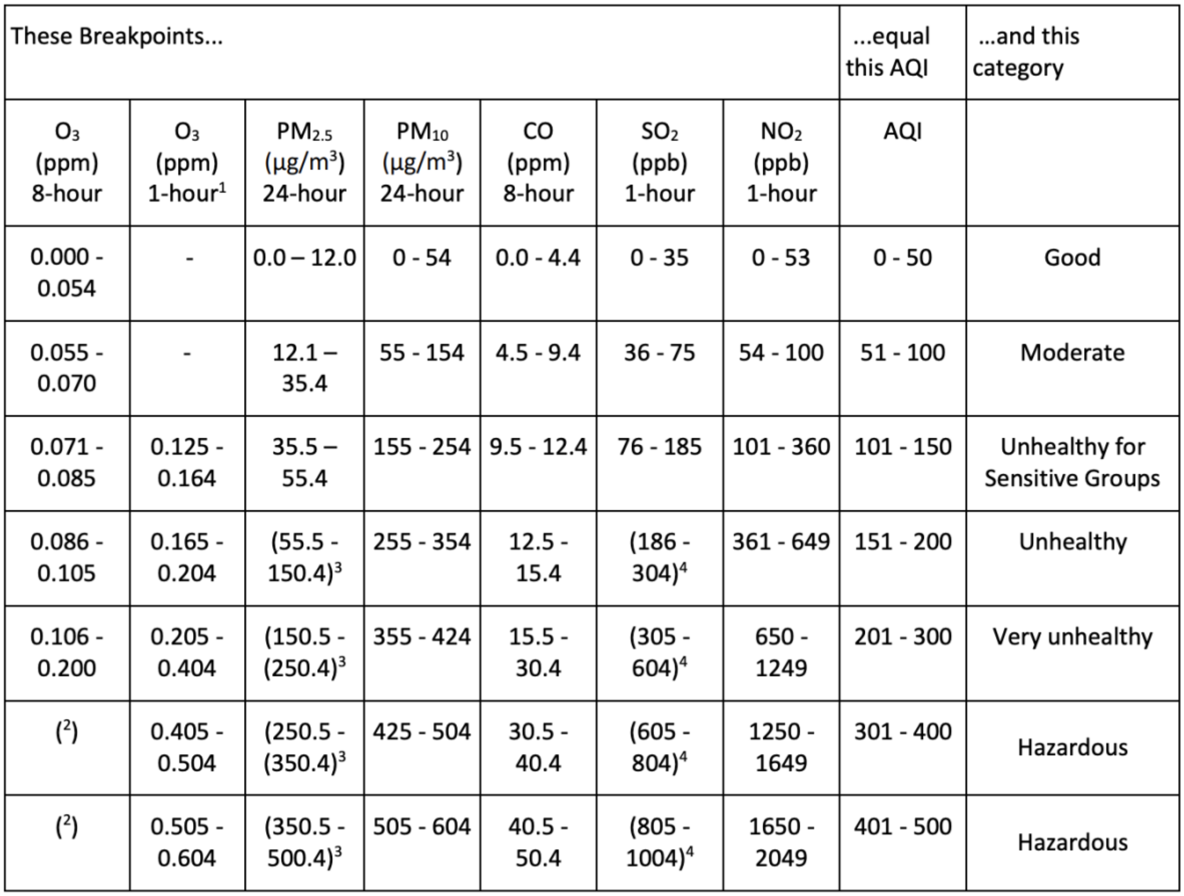
Table S2: Building characteristics used in CONTAM simulations.

Factor	**Value**	**Source**
Window-to-Wall Ratio (WWR)	0.18	Lu and Warsinger, 2020
Exhaust fan flow rate	100 scfm (lower end)	Rim et al., 2012
Building Air Change Rate (ACH)	0.35 1/h	Persily et al., 2006

Table S3: Typical California weather conditions used in CONTAM simulations.

Factor	**Value**	**Source**
Wind Speed	1 m/s	Comparative Climatic Data
Outdoor Temperature	21.8℃	Comparative Climatic Data
Indoor Temperature	21.7℃	Booten et al., 2017
Humidity	69%	Comparative Climatic Data

Table S4: Air Quality Index (AQI) breakpoints (US EPA); [1]Areas are generally required to report the AQI based on 8-hour O_3 values. However, there are a small number of areas where an AQI based on 1-hour O_3 values would be more precautionary. In these cases, in addition to calculating the 8-hour O_3 index value, the 1-hour O_3 value may be calculated, and the maximum of the two values reported. [2]8-hour O_3 values do not define higher AQI values (≥ 301). AQI values of 301 or higher are calculated with 1-hour O_3 concentrations. [3]If a different Standard Health Level for $PM_{2.5}$ is promulgated, these numbers will change accordingly. [4]1-hour SO_2 values do not define higher AQI values (≥ 200). AQI values >200 are calculated with 24-hour SO_2 concentrations.



These Breakpoints...							...equal this AQI	...and this category
O_3 (ppm) 8-hour	O_3 (ppm) 1-hour[1]	$PM_{2.5}$ ($\mu g/m^3$) 24-hour	PM_{10} ($\mu g/m^3$) 24-hour	CO (ppm) 8-hour	SO_2 (ppb) 1-hour	NO_2 (ppb) 1-hour	AQI	
0.000 - 0.054	-	0.0 – 12.0	0 - 54	0.0 - 4.4	0 - 35	0 - 53	0 - 50	Good
0.055 - 0.070	-	12.1 – 35.4	55 - 154	4.5 - 9.4	36 - 75	54 - 100	51 - 100	Moderate
0.071 - 0.085	0.125 - 0.164	35.5 – 55.4	155 - 254	9.5 - 12.4	76 - 185	101 - 360	101 - 150	Unhealthy for Sensitive Groups
0.086 - 0.105	0.165 - 0.204	(55.5 - 150.4)[3]	255 - 354	12.5 - 15.4	(186 - 304)[4]	361 - 649	151 - 200	Unhealthy
0.106 - 0.200	0.205 - 0.404	(150.5 - (250.4)[3]	355 - 424	15.5 - 30.4	(305 - 604)[4]	650 - 1249	201 - 300	Very unhealthy
(2)	0.405 - 0.504	(250.5 - (350.4)[3]	425 - 504	30.5 - 40.4	(605 - 804)[4]	1250 - 1649	301 - 400	Hazardous
(2)	0.505 - 0.604	(350.5 - 500.4)[3]	505 - 604	40.5 - 50.4	(805 - 1004)[4]	1650 - 2049	401 - 500	Hazardous

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