Title

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Executive Summary

The 2007 Energy Independence and Security Act mandated that the U.S. Department of Energy develop energy conservation standards for manufactured housing (MH). The standards would necessarily expand and supersede elements of the Manufactured Housing Construction and Safety Standards set by the U.S. Department of Housing and Urban Development (HUD Code) that are relevant to energy use. The EISA directs DOE to develop the standards based on the most recent version of the International Energy Conservation Code (IECC) or other codes or standards if they are more cost effective. The history of the rulemaking is provided in Docket EERE-2009-BT-BC-0021. In 2021 DOE developed and published several options for public review. Two key elements of all variations of the proposed rule were aimed at reducing uncontrolled air exchange with the outdoors. The first was envelope air sealing that was estimated to achieve air leakage of no higher than 5 air changes per hour (ACH) at 50 Pa indoor-outdoor pressure difference (ACH_{50}), which would improve on the 8 ACH_{50} level assumed as the minimum performance level for MH at the time. The second was prescriptive air sealing measures for the ductwork of forced air heating and air conditioning (HAC) systems that were expected to limit their total air leakage to 4 cubic feet per minute per 100 square foot of conditioned floor area when ducts are pressurized to 25 Pa (cfm25/100sf), improving on the total duct leakage of 12 cfm25/100sf estimated for a HUD Code home (a home meeting the HUD code but not including the efficiency measures of the proposed standard). Estimating that 50% of air leakage from the ducts goes to outside leads to an estimated reduction of duct leakage to outside from 6 cfm25/100sf for the HUD Code home to 2 cfm25/100sf a home meeting the DOE proposed rule.

The National Environmental Policy Act requires the government to consider the potential for significant adverse effects of new regulations, and either reach a finding of no significant impact that is documented in an Environmental Assessment or evaluate potentially significant impacts through an Environmental Impact Statement (EIS). Since air sealing reduces the flow of outdoor air, which serves to dilute and remove air pollutants emitted inside the residence, the proposed rule could lead to higher concentrations and exposures to some air pollutants. At the same time, indoor concentrations of some outdoor pollutants, including NO_2, $PM_{2.5}$, and wildfire smoke could be reduced.

This report presents a simulation-based analysis that estimates the magnitude of indoor air pollutant concentration changes that could result from the proposed energy conservation standards. The analysis was conducted for a 1568 ft^2, double-wide MH with variations in heating and cooling equipment (either furnace + air conditioner or heat pump) and various types of whole-house mechanical ventilation (continuous exhaust fan or central fan integrated supply), in three locations with varying climate conditions: Chicago IL, Fresno, CA; and Houston TX. The simulations tracked four air pollutants that can reach levels exceeding established safe target levels in homes: acrolein, formaldehyde, fine particulate matter ($PM_{2.5}$), and nitrogen dioxide (NO_2). The simulations considered acrolein and formaldehyde emitted from continuous indoor sources; acrolein, NO_2 and $PM_{2.5}$ from cooking; $PM_{2.5}$ from dispersed occupant activities; and NO_2 and $PM_{2.5}$ from outdoors, using historical data to identify typical levels. The impacts in homes operating or not operating whole-house mechanical ventilation equipment, kitchen and bath exhaust fans, and window opening as ventilation approaches were examined.

The analysis found that DOE's proposed standards would lead to substantial improvements in the protection that manufactured homes provide to occupants against outdoor air pollution. Under closed house conditions, with ventilation systems temporarily turned off as recommended during outdoor air pollutant events, homes built to DOE's proposed air tightness standards would have indoor concentrations of outdoor NO_2 and $PM_{2.5}$ that are about 25-30 percent lower than would occur in a HUD Code home.

The analysis also found that concentrations of pollutants from indoor sources may be expected to increase with DOE's proposed standards if all material emissions and behavioral factors are unchanged. The analysis also found that increases would be lower in homes using mechanical ventilation that is required in the HUD Code (and would continue to be required, without changes, in the proposed rule), and that increasing use of mechanical ventilation could lead to lower exposure. Some key findings are noted below:

- For continuously emitted volatile organic compounds, the increase is estimated to be 27–68 percent across all ventilation practices.
- Acrolein and other gases from cooking would increase by 29–76 percent and $PM_{2.5}$ from cooking would increase by 9–51 percent across all ventilation scenarios. NO_2 from gas cooking burners would increase by 9–37 percent across all ventilation scenarios.
- $PM_{2.5}$ from occupant activities would increase by 7–28 percent across all scenarios and by 15–19 percent in homes using continuous exhaust ventilation.
- Increasing the use of ventilation equipment can effectively mitigate the increases in indoor generated pollutants that would otherwise result from improved air tightness of DOE's proposed standards.
- As an example of the benefits of ventilation, the model predicts that with operating continuous whole house mechanical ventilation, average formaldehyde in homes meeting the new airtightness standards would remain below about 23 ppb, similar to levels observed in recent studies of modern, site-built homes with mechanical ventilation. And compared to a HUD Code home that does not use mechanical ventilation, a home meeting DOE's proposed standards that uses continuous exhaust ventilation would have formaldehyde concentrations that are 14 percent lower to 10 percent higher across the three locations.
- Compared to a HUD Code home that does not use mechanical ventilation, a home meeting DOE's proposed standards that uses a range hood during all cooking would have cooking-related acrolein concentrations that are 46–52 percent lower. The reduction would be 55–59 percent lower for NO_2 from gas cooking burners and 53–57 percent for $PM_{2.5}$ from cooking.

Results of modeling described in this report are cited in the Final EIS for the efficiency rule[1], which was published in the federal register (87 FR 32728, pages 32728-32824) on May 31, 2022.

[1] Final Environmental Impact Statement for Proposed Energy Conservation Standards for Manufactured Housing. DOE/EIS-0550D. April 2022.

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1 Introduction

Manufactured Housing (MH), as defined in the National Manufactured Housing Construction and Safety Standards Act of 1974 (42 U.S.C. 5401-5426) (the Act), is a dwelling with minimum dimensions of 8 feet wide by 40 feet long that is built in a factory on a permanent chassis and transported in one or more sections to be erected on site, and contains all necessary plumbing, heating, air-conditioning, and electrical systems.

A 2020 report by the Manufactured Housing Institute (MHI, 2020) noted that a total of 22 million people in the US lived at that time in MH; and in 2019, MH represented 10% of new, single-family home starts, totaling nearly 95,000 units. MH dwellings are most common in rural areas, where they represent 14% of the housing stock (compared with roughly 6% of the US housing stock overall). With an average cost of $55 per square foot (sf), compared to $114/sf for site-built homes in 2018 (MHI, 2020), MH is among the most affordable options for new home purchase.

The 1974 law directs the U.S. Department of Housing and Urban Development to establish standards for the design, construction, and installation of manufactured homes to assure their quality, durability, safety, and affordability. These standards (the "HUD Code") supersede any state and local regulations for the covered housing units. The first standards were published in the Code of Federal Regulations in 1976 as 24 CFR part 3280 and they have been updated numerous times since then. The Manufactured Housing Improvement Act of 2000 amended the 1974 Act by creating new requirements for installation and dispute resolution, and mandated that the Secretary establish the Manufactured Housing Consensus Committee (MHCC) to provide recommendations regarding adoption, revision, and interpretation of the standards and procedures for enforcement. The HUD Code includes many provisions that impact energy efficiency[2] and a major revision in 1994 included requirements for mechanical ventilation to protect indoor air quality. There were specific requirements for whole house mechanical ventilation at specified minimum rates and also for kitchen and bath exhaust fans.

As a complement to the HUD Code, Section 413 of the Energy Independence and Security Act of 2007 (EISA) directed the U.S. Department of Energy (DOE) to establish and regularly update standards for energy conservation in manufactured housing. The EISA directs DOE to base the standards on the most recent version of the International Energy Conservation Code (IECC), except where DOE finds that the IECC is not cost effective, or a more stringent standard would be more cost effective, based impacts to the purchase price of manufactured housing and on total life-cycle construction and operating costs.

A brief history of DOE's efforts to implement this mandate is provided in the Final Environmental Impact Statement (DOE/EIS-0550) for proposed approaches to a rule that will be issued in 2022.[3] Key elements of the IECC are specific limits of air-tightness for the building envelope and the air distribution ductwork of any forced air thermal conditioning system. The specific requirements in the proposed rule are as follows:

1. Prescriptive envelope air sealing requirements that are expected to achieve a maximum air leakage of 5 air changes per hour at 50 Pa indoor-outdoor pressure difference (ACH_{50}. Estimated baseline envelope leakage for the HUD code is 8 ACH_{50}.
2. Prescriptive duct air sealing requirements that are expected to achieve a maximum air leakage of the central forced air heating and air conditioning (HAC) system of 0.044 cubic feet per minute (cfm) per square foot of conditioned floor area (CFA) when ducts are pressurized to 25 Pa (cfm25/sf). Estimated baseline duct leakage for the HUD code is 0.12 cfm25/sf.

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[2] See 24 CFR 3280.507(a), specifying thermal insulation requirements; and 24 CFR 3280.508(d), detailing efficiency requirements for heating and cooling equipment in manufactured homes.
[3] https://www.regulations.gov/docket/EERE-2009-BT-BC-0021/unified-agenda

When envelopes are tightened, natural air exchange with the outside also is reduced. The reduced flow of outdoor air over time leads to higher indoor concentrations of pollutants that are generated indoors, if all other factors are held constant. Outdoor (ambient) pollutants without indoor removal processes will have the same long-term concentrations indoors as outdoors regardless of air infiltration or ventilation rate. Outdoor pollutants that are removed from indoor air via processes other than ventilation (such as deposition to surfaces and filtration) will have lower concentrations indoors when air leakage is reduced. A building envelope with less leakage enables improved control of exposure to outdoor pollutants. These processes raised the possibility that the air tightness requirements could cause substantial changes to air pollutant concentrations in manufactured homes that would impact resident health risks; and the evaluation of such potential impacts is a requirement of the National Environmental Policy Act of 1970. This report details an analysis that was conducted for this purpose.

MH are required by HUD code to have whole-house mechanical ventilation (WHMV) equipment with capacity of 0.035 cfm per square foot of floor area, subject to minimum and maximum flows of 50 and 90 cfm, respectively (3280.103(b)). The HUD code specifies that a label must be installed adjacent to the switch controlling the WHMV that reads "Whole House Ventilation" (3280.103(b)(5)). The HUD code also requires that the homeowner's manual provide "instructions for correctly operating and maintaining whole-house ventilation systems" and the instructions "must encourage occupants to operate these systems whenever the home is occupied, and must refer to the labeled whole-house ventilation control" (3280.103(b)(6)). This mechanical ventilation can mitigate potentially negative impacts of reduced envelope leakage and natural ventilation air flows associated with the proposed rule. But if ventilation equipment is not operated continuously, as intended, then reduced airflow and potentially worsened IAQ remain a possibility under the proposed rule. The MH code also requires kitchen and bathroom exhaust fans with minimum airflows of 100 cfm and 50 cfm, respectively, which can be used to remove water vapor and contaminants emitted from cooking or bathing. It should be noted, however, that there is no requirement for verification of these airflows and measurements have found that bath fans in some existing homes don't provide the required airflows (Government Accountability Office, 2012; Pigg et al., 2016).

Available public information and input from industry experts indicate that there are two types of whole house mechanical ventilation (WHMV) equipment commonly used in most MH. Each of these types are discussed in greater detail below. The assessment of whether a manufactured home design meets the HUD Code requirements is made by a contracted Design Approval Primary Inspection Agency (DAPIA), which reviews plans including equipment specifications. The code does not specify a requirement for ventilation airflow verification and it is at the discretion of the DAPIAs to determine if the equipment specified in a design meets the requirement.

The most common type of WHMV is the central fan integrated supply (CFIS), which is sometimes referred to as Positive Operating System or POS (Evcon) or Ventilaire (Nordyne). This entails a duct connected between outdoors and the return side of the forced air heating and cooling system (HAC). When the central HAC fan operates, a negative pressure is induced on the return side of the HAC system, drawing air from outside into the return duct or sealed closet which contains the HAC system (and making it into an HVAC system, with the "V" representing ventilation). The air is tempered by the heating/cooling system and mixing with indoor air. This mixture of outside and recirculated house air is distributed via the supply duct system. This approach is intended to induce a slight positive pressure in the home with respect to outside; however, due to air leakage from the supply side of the forced air ductwork, the house can be depressurized even with the outdoor air inlet. The HUD code includes a requirement that the homeowner manual advise continuous operation of the mechanical ventilation system whenever the dwelling is occupied, but the code only requires that system be capable of operating continuously. This could be accomplished with a thermostat that has a control mode to operate the central HAC system fan or a more sophisticated controller, e.g., to operate the system intermittently if the airflow during operation is sufficiently large to meet the requirement with only partial run time. If the control for continuous or intermittent operation is not activated, ventilation is induced only during the times that the system is operating for heating and cooling. Note that when the system is operated for ventilation only there is not heating or cooling and thus less tempering of the ventilation air. Annual HAC system runtime in US homes is typically on the order of 18% (Touchie & Siegel, 2018), meaning that opportunistic CFIS does not ventilate the homes for roughly 82% of annual hours. Furthermore, runtime occurs during colder/hotter periods, when natural infiltration air flows are typically higher. This approach increases outside air ventilation rates during the hottest and coldest weather, increasing HAC energy use, and it also fails to ventilate the home during times when natural ventilation is at its lowest (i.e., during mild weather periods). CFIS systems can be programmed to operate the central HAC fan every hour of the year, but this is uncommon, as it can be noisy, produce uncomfortable drafts, consume substantial energy for operating the HAC fan[4] and incur higher utility bills. In addition, outside air inlets can be blocked by plant materials, reducing airflow over time (Sonne et al., 2015). CFIS systems benefit from distributing outside air throughout the home (e.g., to bedrooms with closed doors), mixing indoor air to alleviate any localized odor or pollution issues, avoiding drawing air from attached spaces that may be polluted (e.g., attics, crawlspace, garages) and providing filtration when a filter designed to remove airborne fine particulate matter is installed and maintained in the HAC system. Importantly, there is no requirement in the HUD Code for verification of the airflow provided by a CFIS system.

The other common WHMV system is an exhaust fan that operates continuously or intermittently each hour to provide airflow. Exhaust fans induce a negative pressure across leaks throughout the building envelope, and outside air is drawn indoors through those leaks. Leaks can occur anywhere throughout the building, including between the living space and the attic, between the living space and belly (e.g., via plumbing penetrations), through leakage in ducts, around windows, etc. Some contaminants in outside air are removed as they travel through leakage sites in the building envelope, which can reduce indoor exposures to outdoor pollutants. Incoming air flows may also include emissions from attached spaces (e.g., biological contaminants from the attic) or from the building envelope itself (e.g., formaldehyde from composite wood products used in structural framing). Outside air is distributed in the sense that leakage sites are distributed, but the amount of airflow through any given leak depends on pressure interactions driven by weather conditions (e.g., wind speed and direction), leakage location and by configuration of the home (e.g., doors open vs. closed or 1- vs. 2-story locations).

In this context of reduced natural infiltration associated with the proposed rule, and mechanical ventilation technologies commonly found in MH, it follows that the greatest increases in indoor-generated contaminants (and the greatest reductions in contaminants of outdoor origin) is expected to occur in MH that do not continuously use WHMV and do not routinely open windows. However, the dynamics are complex. The net impact on exposure to a contaminant like fine particulate matter, which has both outdoor and indoor sources, will depend on numerous interrelated factors, including HAC runtime, flow and filter efficiency, use of kitchen exhaust fans, and the frequency and quantity of cooking and other indoor sources, etc. The net impacts cannot be determined simply, so a detailed simulation effort to address a subset of questions related to ventilation and IAQ in MH is justified.

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[4] The incremental cost of operating a CFIS ventilation system "whenever the home is occupied", including times when the HVAC system is not needed for thermal conditioning, can be substantial. Assuming the central HAC system runs for roughly 20% of the time throughout the year, the fan would need to operate for approximately 7000 additional hours (0.8*8760) to provide ventilation. Assuming a 310 W power draw (based on calculation noted below from DOE furnace blower rule), the cost would be $230 per year to operate the central HAC fan for ventilation purposes. In contrast, the cost to operate a 50 cfm continuous exhaust fan with efficacy of 2.8 cfm/W for all 8760 hours of the year is $17 per year. In addition to fan energy operating cost differences, the continuous CFIS system also incurs substantial additional heating and cooling load due to the energy losses associated with duct leakage. These additional losses would also increase household energy operating costs for MH using continuous CFIS systems. *Note: The DOE furnace fan rule (10 CFR Parts 429 and 430) requires a Fan Energy Rating (FER, watts per 1000 cfm) of 0.07*Qmax+240. For Qmax=1000cfm, the FER would be 310 watts.*

The overarching goal of this work was to develop quantitative estimates of the impacts that DOE's proposed energy efficiency requirements might have on air pollutant concentrations in manufactured homes given a fixed set of common conditions. We designed our simulation analysis around the following specific objectives:

1. Estimate air pollutant concentrations in MH resulting from a suite of discrete indoor source types and pollutants entering from outdoors under various scenarios of mechanical and natural ventilation.
2. Estimate *changes* in indoor air pollutant concentrations that will result from changes to envelope and duct air tightness under scenarios described in #1.
3. Conduct the analysis for homes that minimally meet the requirements of the current HUD Code and the air tightness requirements of the proposed DOE rule.
4. Conduct analysis for manufactured homes sited at locations that represent each of the three HUD climate zones and a substantial fraction of the climate variability within the U.S.
5. Quantify the impacts of WHMV equipment selection and use on the calculated concentrations under each air tightness condition, and consider the potential for increased ventilation use (either whole house or local exhaust) to mitigate any significant changes to pollutant concentrations that would otherwise occur resulting from increased airtightness.

2 Method

This modeling work was designed to estimate the magnitude of potential indoor air quality impacts resulting from proposed DOE energy efficiency rules, specifically focusing on the impacts of reduced air leakage in the building envelope and duct system. Previous energy analysis was performed in support of the proposed DOE rule by researchers at Pacific Northwest National Laboratory (PNNL) to determine the impacts on energy use. Our modeling is a follow-on effort that uses the simulation files developed by PNNL, refines them for ventilation and IAQ modeling, and leverages enhanced tools for predicting airflow and contaminant transport.

Our modeling framework was designed to calculate indoor concentrations of four air pollutants in manufactured homes and also to estimate air exchange with outside. The specific pollutants were selected based on the potential for indoor household exposures to harm human health. In addition, the pollutants are generally representative of broader pollutant source categories (e.g., by-products of combustion, volatile organic compounds emitted from building materials). Appropriate estimation of the relevant airflows and pollutant concentrations under various air leakage and ventilation scenarios required the use of two simulation tools: Energy Plus and CONTAM. Shared inputs were used for both simulation tools in order to represent an average, newly constructed manufactured home. The simulation inputs included envelope and duct air leakage, pollutant emission rates and other parameters derived from the published research literature.

Five parameters were varied in the simulation effort in order to estimate the ventilation and IAQ impacts of the proposed rule:

- Climate zone (Chicago, IL; Fresno, CA; and Houston, TX);
- Thermal envelope performance, including insulation and air leakage of building envelope and HAC ducts (HUD code vs. Tier 2 of Proposed Rule);
- Operation of mechanical equipment and windows to provide ventilation, including:
    - Whole House Mechanical Ventilation type and usage (continuous exhaust, continuous CFIS and runtime CFIS),
    - Local exhaust ventilation usage (None and "Recommended", i.e. use of kitchen exhaust ventilation during all cooking and use of bath exhaust at the frequency assumed for bathing),

- ○ Window operation (None and During Mild Weather);
- HAC equipment type (Heat pump and Furnace + air conditioner, AC);
- Ambient pollution levels (50th and 98th percentile);

All simulations shared the same inputs for the following:

- Home prototype geometry
- Indoor pollutant emission rates, schedules and loss mechanisms
- Occupancy

The details of the simulation tools, modeling assumptions and parameters are described in further detail in subsections below. First, we describe the simulation inputs that characterize the prototype building geometry and mechanical systems (see Section 2.1). Second, we characterize the emission sources of pollutants in the modeling see Section 2.2). Finally, we describe the simulation framework that combines inputs and outputs for the two tools into a single workflow capable of representing the dynamics of the air leakage and ventilation scenarios (see Section 2.3).

2.1 Dwelling Characterization Inputs

2.1.1 Locations

Three locations across the US were selected for modeling: Fresno, CA, Houston, TX, and Chicago, IL. The locations are summarized by climate zone, heating and cooling degree days and ambient pollution levels in Table 1, and the locations are shown on maps of US DOE climate zones and of HUD climate zones in Figure 1 and Figure 2, respectively. The outdoor weather data for each location were extracted from the Typical Meteorological Year (TMY) data from Energy Plus weather files, which contain one year of hourly data that best represents median weather conditions over a multi-year period.

These locations were chosen because they are representative of climate regions with substantial populations of manufactured homes, and weather patterns in the three climate zones represent important dynamics related to ventilation and indoor air quality, namely the impact of ambient temperatures on the magnitude and direction of natural air exchange through envelope leakage pathways. The TSD summarizes total shipments by climate zone, with zones 1, 2 and 3 representing 38, 29 and 34% of national shipments, respectively. The location with the greatest percent of shipments within each climate zone was selected for our modeling. Notably, in order to represent high ambient particle pollution, we used the Fresno, CA location in place of the El Paso, TX location from the DOE energy analysis. Both locations were deemed to have similar climate patterns and housing characteristics. The Fresno, CA EnergyPlus modeling inputs were derived from the existing El Paso, TX files.

Table 1 Locations selected for illustrative simulations.

Location	Region	HUD thermal zone	DOE climate zone	Heating degree days, base 65ºF (HDD_{65})[2]	Cooling degree days, base 65 ºF (CDD_{65})	Heat set point (°C)	Cooling set point (°C)	Mean $PM_{2.5}$ AQ sites	Mean NO_2 AQ sites
Chicago	Midwest	4	3	6493	1010	19.2	24.1	9.0	13.3
Fresno[1]	Southwest	3	2	2647	2362	19.6	25.4	11.0	8.3
Houston	Central south	1	1	1681	3012	20.1	24.3	8.4	5.6

[1] The simulation for Fresno was done with an EnergyPlus model that DOE developed and used for energy and cost analysis in El Paso, TX which is in the same HUD thermal zone, and has similar HDD (2300) and CDD (2521) as Fresno.

[2] Heating and cooling degree days as ºF--day, base 65ºF (HDD65 and CDD65, respectively); these are calculated from the TMY weather files used in the simulation analysis. Locations with milder climates have fewer combined heating and cooling degree days and are more likely to use natural ventilation (open windows), with increased air exchanges reducing the impact of indoor emission sources on indoor air quality.

Each location (Chicago, Fresno and Houston) used unique thermostat setpoints based on median values reported for Building America climate zones in a previous study (Huchuk et al., 2018). The details about the cooling and heating set points for each location are shown in Table 1.

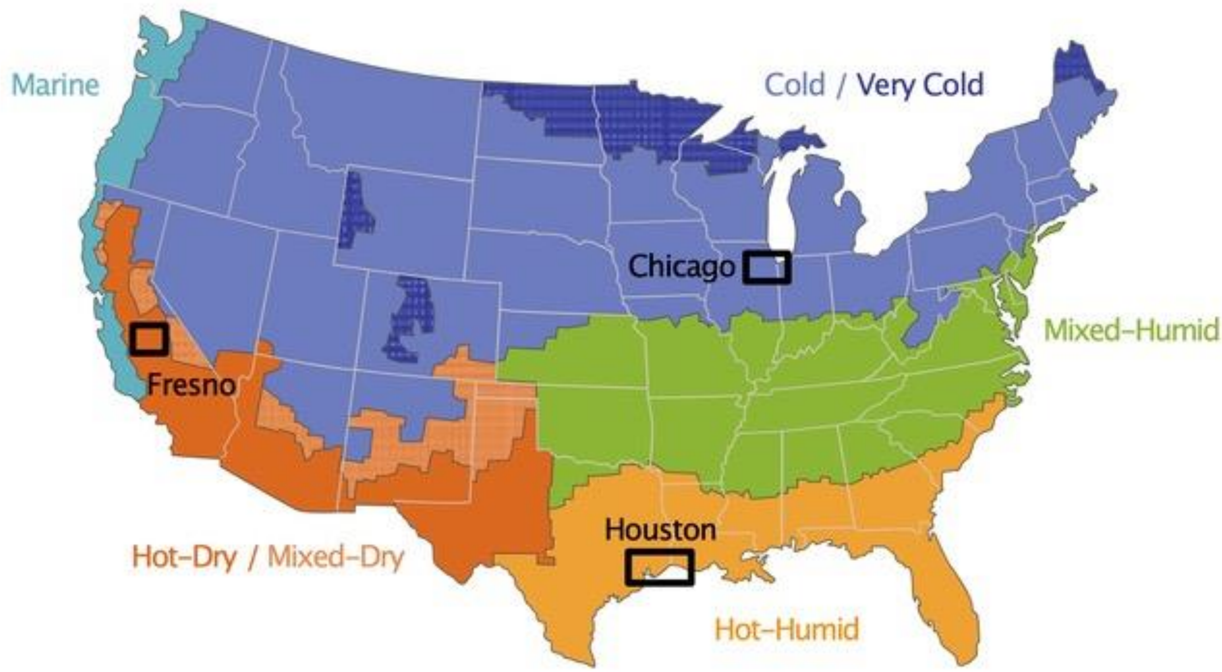

Figure 1 Map of US DOE Climate Zones and simulation locations.

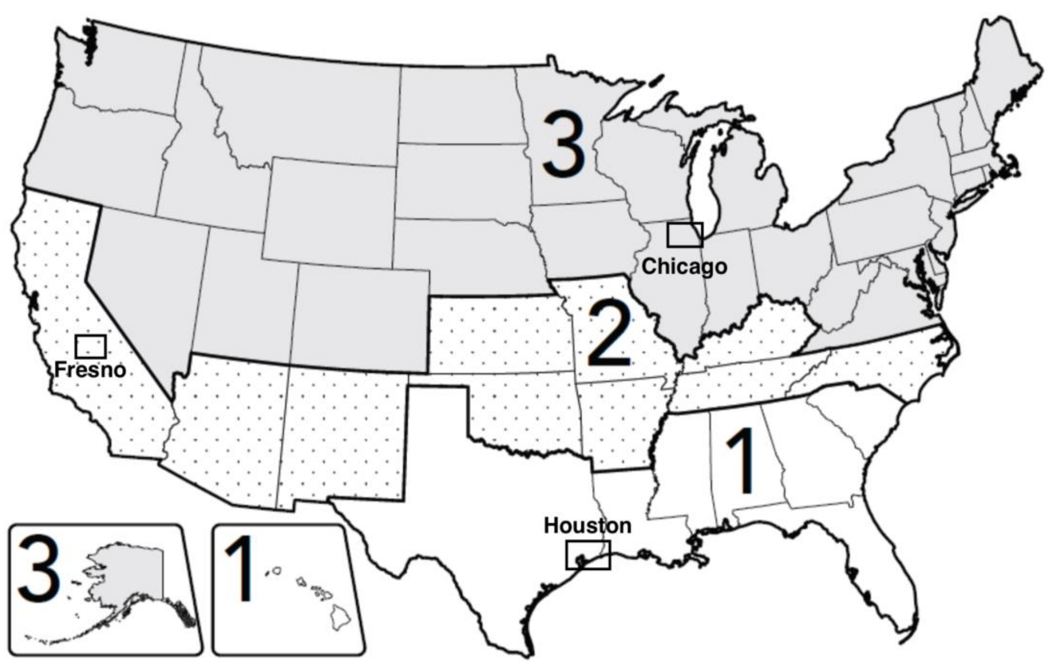

Figure 2 Map of HUD Climate Zones for Manufactured Homes and simulation locations.

2.1.2 House Prototype and Occupancy

The Manufactured Housing Institute (MHI) reports that average new MH sold since 2014 were 1,400-1,500 ft^2 (MHI, 2020), with substantial differences between single- and double-section units. Recent DOE energy modeling in support of the proposed rule represented both single- and double-section units (US DOE, 2021), assuming a single-section manufactured home to be 14 ft by 66 ft (924 ft^2) and double-section units to be 28 ft by 56 ft (1,568 ft^2). For both modeled prototypes, these floor areas are smaller than those reported by MHI of the new MHs built since 2014. Our goal was to leverage the existing modeling efforts of DOE, while reasonably representing new shipments of MH in the past half-decade. As a result, our modeling focused on the larger, double-section prototype, which aligns better with the MHI data. The same double-section, 1,568 ft^2 building prototype was represented in both EnergyPlus and CONTAM. Manufactured homes can also have three or more units in width; however, the 2019 American Housing Survey (AHS) indicates that triple-section manufactured homes account for only 1.5 percent of all manufactured homes (US Census Bureau, 2019). Based on data from the 2019 AHS, the prototype double-section MH was assumed to have a laundry room with a vented clothes dryer, along with two full bathrooms with local exhaust fans.

The modeling of home occupancy is important for reflecting internal heat gains and contaminant emissions that are occupant-dependent (e.g., cooking or candle burning). The 2015 Residential Energy Consumption Survey (RECS) showed an average of 2.6 occupants per MH (US EIA, 2015). Similarly, the 2019 AHS showed an average of 2.3 occupants per MH. Representation of partial occupants was deemed inappropriate for our purposes, so we assumed three occupants in all cases. We assumed occupants were in the dwelling every day, with active and awake hours between 7 am and 11 pm. Details about the MH size and occupancy in the modeling are summarized in Table 2.

Table 2 Summary of the house and occupancy parameters of the MH prototype in the modeling.

Parameter	**Assumption**
House type	Double section
Floor Area (ft^2)	1568
Number of People	3
Occupancy Pattern	Always at home
Occupants awake / active	07:00-23:00
Number of each meal cooked per week (number with PM emitted)	Breakfast: 7(4); Lunch: 5(2); Dinner: 7(5)
Number of bathrooms	2
Dryer exhaust fan	1

2.1.3 Thermal Envelope Characteristics

The thermal performance of the exterior envelope of manufactured homes has important impacts on building loads and associated HAC equipment sizing, airflows and runtime. We simulated two sets of thermal envelope characteristics, representing the current HUD code and Tier 2 of the proposed rule. For each climate zone and envelope element, the thermal performance requirements of the current HUD code, those of the proposed rule (i.e., Tier 1 and Tier 2) and those used in our modeling are reproduced in The EnergyPlus models provided by PNNL were variations of those models described in the 2021 TSD. We identified minor differences in envelope insulation values between the Tier 2 and model inputs for this study. These are shown in the “This study” column in Table 3.

Table 3 Comparison of component requirements with HUD Code baseline.

City	Thermal Envelope Element	HUD Code	Proposed Rule - Tier 1	Proposed Rule - Untiered/ Tier 2	This study
Chicago	Exterior Wall Insulation R-value	13	19	20+5	21
	Exterior Ceiling Insulation R-value	30	22	38	38
	Exterior Floor Insulation R-value	22	22	30	30
	Window U-factor	0.35	0.35	0.30	0.32
	Window SHGC▫	0.33	NR(0.33)	NR(0.25)	0.33
	Domestic Hot Water Pipe Insulation	NR	R-3	R-3	R-3
El Paso	Exterior Wall Insulation R-value	11	13	20+5	20
	Exterior Ceiling Insulation R-value	22	22	30	30
	Exterior Floor Insulation R-value	19	19	19	19
	Window U-factor	0.5	0.5	0.3	0.3
	Window SHGC	0.6	0.6	0.25	0.25
	Domestic Hot Water Pipe Insulation	NR	R-3	R-3	R-3
Houston	Exterior Wall Insulation R-value	11	13	13	13
	Exterior Ceiling Insulation R-value	22	22	30	30
	Exterior Floor Insulation R-value	22	22	13	13
	Window U-factor	1.08	1.08	0.32	0.35
	Window SHGC	0.7	0.7	0.33	0.33
	Domestic Hot Water Pipe Insulation	NR	R-3	R-3	R-3

Units: Exterior Wall Insulation R-value: (hr-ft^2-°F/Btu) Exterior Ceiling Insulation R-value: (hr-ft^2-°F/Btu) Exterior Floor Insulation R-value: (hr-ft^2-°F/Btu) Window U-factor: (Btu/hr-ft^2-°F)

2.1.4 House Envelope and Duct Leakage

Specifications for envelope and duct leakage are shown in Table 4. The envelope leakage (ACH_{50}) and duct leakage (cfm_{25}/100sf) values used in our modeling were aligned with those used in DOE's energy modeling, but we adjusted them to better represent contaminant transport and air exchange phenomenon that were the focus of this work. Specifically, the duct leakage was adjusted to focus on leakage to outside of the occupied volume of the house (living space).

The existing HUD code does not specify maximum envelope air leakage or duct leakage requirements. To overcome this limitation, DOE's energy analysis of the proposed rule set the HUD code baseline leakage at 8 ACH_{50} and total duct leakage to 12 cfm_{25} per 100 ft^2 of conditioned floor area (cfm_{25}/100) (see TSD Table 6.6), based on common industry practice in discussion with the MH working group. The DOE proposed rule does not require envelope air leakage or duct leakage to be tested. Instead, a set of prescriptive, visually-inspected air sealing measures are specified, which the MH working group determined would lead to no greater than 5 ACH_{50} of envelope leakage and 4 cfm_{25}/100 of total duct leakage.

The EnergyPlus thermal modeling included simplified treatment of air exchange through envelope leaks using the effective leakage area values reproduced in Table 4 below. This envelope leakage was represented using ZoneInfiltration:EffectiveLeakageArea objects in EnergyPlus. We adjusted the stack and wind pressure coefficients that were used in the energy analysis of the proposed rule to better represent single-story MH. The EnergyPlus thermal modeling did not include any heat losses or gains representing duct leakage. EnergyPlus modeling included only the current HUD code and proposed rule envelope leakage rates.

The primary adjustment we made to the assumed leakage values from the DOE modeling was to translate total duct leakage to duct leakage to outside, ignoring leaks inside the conditioned space and belly of the MH. Those leaks are not expected to impact air exchange rates or pollutant concentrations in a predictable manner. Previous field research on manufactured houses built since 2000 in Minnesota has shown that the typical duct leakage to outside in MH is about 10% of the heated supply air. Newer MHs appear to have duct leakage roughly half that found in older homes (Pigg et al., 2016). The remaining leakage may open to the belly area and other conditioned indoor spaces of the house, but the location and importance of these leaks has not been well documented. Thus, in our models, we assumed 50% of the total duct leakage was to outside. We translated the total leakage values from the HUD code and proposed rule (12 and 4 cfm_{25}/100, respectively) to leakage to outside values of 6 and 2 cfm_{25}/100, respectively, which are listed in the table below.

Table 4 Scenarios of envelope tightness and duct leakage used in the modeling.

Leakage combinations	**Envelope Leakage Rate (ACH_{50})**	**Effective Leakage Area (in^2)**	**Total Duct Leakage (cfm_{25}/100sf)**	**Duct Leakage to Outside (cfm_{25}/100sf)**
HUD minimum	8	86.02	12	6
DOE minimum	5	53.76	4	2

2.1.5 Heating and Cooling Equipment

In our modeling of ventilation and IAQ, the only important impacts of HAC equipment type are the system runtime and corresponding airflows. These parameters account for air exchange through duct leakage, runtime for CFIS ventilation systems, and recirculation and filtration of air. The DOE energy analysis looked at five variations of HAC system in each location, including: electric resistance heaters, air-source heat pumps, natural gas furnaces, LPG furnaces, and oil furnaces. The types of HAC system were weighted for each area by sales (US DOE, 2021). Heating system runtime is expected to be identical for properly sized conventional furnaces using any fuel type (NG, LPG, Electric, Oil), so heat pumps are the only equipment type with different runtime profiles. Compared with conventional furnaces, heat pumps commonly have lower supply air temperatures in heating mode, so they require greater airflow rates or increased runtime to meet the same load. Consistent with this, we considered only two variations for the HAC system in our model: (1) heat pump and (2) a combination of furnace and air conditioning.

For all locations and envelope performance levels, we searched for actual equipment available on the market that met the requirements of heating and cooling loads calculated from Energy Plus auto-sizing. The details of loads, equipment selection, and corresponding CFIS airflow adjustment are characterized in

Table 5. In all cases, we assumed the HAC system had a single speed fan with fixed airflow, which was used in both heating and cooling modes. This corresponds to the lowest first cost systems on the market. The equipment airflows were set to the maximum required of either the actual heating or cooling equipment selected. Based on these airflow rates, we then manually adjusted the size of the leakage path to outside on the return side of the HAC system in CONTAM to precisely meet the 55 cfm requirement.

Table 5 Summary of the heating and cooling equipment used in the modeling.

Area	Equip-ment	EnergyPlus Load (Btu/hr) HUD/DOE	Capacity (Btu/hr) HUD/DOE	HAC Equipment Model[1]	HAC Airflow (cfm) HUD/ DOE	Eqpt Sizing Fraction, Ef[2] HUD/DOE
Chicago	AC	15170/ 13421	22800/ 22800	M024U-B/ M024U-B	730/ 730	0.67/ 0.59
	Furnace	30768/ 23101	46000/ 46000	M1MB-056/ M1MB-056		0.67/ 0.50
	Heat pump	Cooling: 15170/13421 Heating: 30768/23101	23600 /23600	MX24U/ MX24U	980/ 980	Cooling: 0.67/0.59 Heating: 1.0/1.0
Houston	AC	25992/ 16786	28400/ 22800	M030U-B/ M024U-B	1140/ 930	0.92/0.71
	Furnace	16754/ 11378	46000/ 46000	M1MB-056/ M1MB-056		0.36/0.25
	Heat pump	Cooling: 25992/16786 Heating: 16754/11378	28000 / 23600	MX30U/ MX24U	1200/ 980	Cooling: 0.92/0.71 Heating: 0.60/0.49
Fresno	AC	24278/ 16983	28400/ 22800	M030U-B/ M024U-B	1140/ 930	0.87/0.74
	Furnace	13400/ 9608	46000/ 46000	M1MB-056/ M1MB-056		0.29/0.21
	Heat pump	Cooling: 24278/16983 Heating: 13400/9608	28000 / 23600	MX30U/ MX24U	1500/ 1130	Cooling: 0.87/0.74 Heating: 0.48/0.42

[1] Model numbers of Nortek/Miller equipment. Obtained during January 2022 from the following site: https://literature.nortekhvac.com/Miller.

[2] This is the ratio of the design load to equipment capacity, resulting from the practical limit that equipment is only available in discrete sizes. *Ef* is used in post-processing calculations to adjust runtime estimates from EnergyPlus based on actual equipment sizes, duct leakage and CFIS runtime airflows. When this value reaches 1.0, which only occurs for heat pumps, the system needs to run continuously and a supplemental heat strip will cycle on/off. See post-processing description in Section 2.3.2.

2.1.6 Whole House Mechanical Ventilation

The Whole House Mechanical Ventilation (WHMV) system is intended to set a minimum outside air flow to manage IAQ in MH. Our modeling represents the two most common WHMV systems used in MH, including: (1) simple exhaust fans, and (2) supply systems that use a dedicated outside air duct connected to the return-side of the HAC (CFIS), which draws outside air into the HAC airstream during central fan operation and then distributes it to the living space through the supply duct system. From these two system types, three WHMV configurations were implemented: (1) continuous exhaust, (2) continuous CFIS and (3) runtime CFIS (ventilation occurs only during heating and cooling runtime).

The target WHMV flow rate was 55 cfm (1,568 ft^2 * 0.035 cfm/ft^2). All thermal modeling in EnergyPlus using input files shared by PNNL estimated outside air mechanical ventilation by modeling a simple exhaust fan at 55 cfm in all cases. In CONTAM modeling, exhaust fan flow rates were also set to 55 cfm, and CFIS systems used orifices that were precisely adjusted to deliver exactly 55 cfm of outside air during central fan runtime periods. In actual manufactured homes, WHMV airflows are not set to be precisely equal to the required minimum, largely because available equipment sizes are discrete (e.g., common sizes for exhaust fans are 50 or 80 cfm) and also because the flow resistance of ducting impacts the rated fan airflow. The end result for a simple exhaust or supply fan system is that the installed WHMV airflows may be larger than the required minimum to ensure compliance. For example, 13 of 15 California site-built homes measured by (Stratton et al., 2012) had installed WHMV airflows that exceeded minimum requirements. In a follow-up study in California, the majority of homes (64 of 70) met WHMV requirements with an exhaust fan and all but two of the exhaust fans exceeded the minimum required airflow (Singer et al., 2020). On average, the exhaust fans moved 50% more air than required (ibid). CFIS systems are even more complicated in real world installations, because HAC equipment often has multiple fan speeds and the ducts connected to outside are not precisely adjusted. (Sonne et al., 2015) measured 11 CFIS systems in Florida single-family homes, and they found that almost all delivered less outside air than was expected based on the equipment ratings.

Local exhaust fan flows were specified to comply with minimum requirements in the HUD code, including 100 and 50 cfm in kitchens and bathrooms, respectively. The vented clothes dryer was deemed to have 125 cfm of exhaust flow during operation. Window opening was modeled as two openings on adjacent sides of the dwelling. Variations were introduced for usage of these local ventilation options, including bathroom exhaust fans (no use vs. use when bathroom occupied), kitchen range hood exhaust fans (no use vs. use when cooking) and window operation (no use or occurring when the HAC system was off for at least 6 hours). The clothes dryer was vented to outside with the same assumed operating time in all cases. The scheduling of these local exhaust fans and window operation are detailed in subsections below. Local exhaust fans, the vented clothes dryer and window operation were implemented only in CONTAM; they were not included in EnergyPlus thermal modeling of system loads, airflow and runtime.

In total, eight ventilation scenarios were assembled from the combination of WHMV systems described above, along with local exhaust and window options. The matrix of these combinations is shown in

Table 6.

HUD code requires “balanced mechanical systems" but also allows supply- or exhaust-only systems. To be considered “balanced mechanical systems” both of our WHMV systems would require passive inlets (e.g., pressure relief damper or wall inlet). The actual prevalence of these dampers across the U.S. was not determined and our modeling did not include pressure relief inlets, which has some impact on the path of outside make-up air when the dwelling is depressurized by exhaust fan operation. Particle pollution passing through relief vents is expected to penetrate indoors with 100% efficiency (i.e., no losses), while our modeling without the relief vents imposes a 20% loss mechanism for PM entering with infiltrating air (see Section 2.2.5 for more details), based on Singer et al. 2020. However, we anticipate that only a small fraction of the make-up air actually passes through relief inlets vs. other leaks in the building envelope. The impact of changing penetration on indoor pollutant concentrations would be even smaller.

Table 6 Ventilation scenarios in the simulation.

Scenario Name	WHMV System	Kitchen range hood	Bathroom exhaust	Laundry exhaust	Window use
Minimal use of ventilation (CMN)	CFIS runtime	Off	Off	On	No
Minimal with window (CMW)	CFIS runtime	Off	Off	On	Yes
Suggested (CSN)	CFIS runtime	Used when cooking	On	On	No
Suggested with window (CSW)	CFIS runtime	Used when cooking	On	On	Yes
Continuous CFIS only (CCN)	CFIS continuous	Off	Off	On	No
Continuous exhaust fan only (ECN)	Exhaust fan continuous	Off	Off	On	No
Full ventilation CFIS (CFN)	CFIS continuous	Used when cooking	On	On	No
Full ventilation, exhaust fan (EFN)	Exhaust fan continuous	Used when cooking	On	On	No

2.1.6.1 Dryer Exhaust Fan Use

Use of a vented clothes dryer was assumed in all scenarios. The total amount of dryer use in a week was specified based on measurements collected over a period roughly one week in each of 70 modern California single, detached homes, as reported by (Chan et al., 2019). The mean and median weekly dryer usage in that study were 2.2% and 1.8%, corresponding to 3.7 and 3.0 hours per week, or 32 min and 26 minutes per day. The dryer was assumed to exhaust 125 cfm based on an Energy Star report (estimated as 100-150 cfm in Table 2) (US EPA, 2011). Since the timing of clothes dryer use varies across households, the dryer exhaust flow was translated to a continuous airflow over the 16-h period of 7 am to 11 pm each day, corresponding to assumed waking hours. The continuous flow was set to 4.2 cfm based on 32 minutes per day of usage.

2.1.6.2 Bath Exhaust Fan Use

In 53 single-family new California homes where the bathroom fans were not used as whole house ventilation fans, the mean and median bathroom fan use were 160 min and 89 minutes per day, respectively (Chan et al., 2019). These new single-family homes have lower occupant densities than typical MH, so we used the 75th percentile values for bathroom fan operation (190 minutes per day) in this modeling. The minimum 50 cfm bathroom fan flow rate for 190 minutes per day was distributed into the 16 hour waking period from 7 am to 11 pm, resulting in a constant flow of 10 cfm during those times. We also considered scenarios with no bathroom fan use.

2.1.6.3 Kitchen Exhaust Fan Use

A 100 cfm range hood exhaust fan was set up in the CONTAM model to be compliant with the HUD minimum requirement. The range hood was assumed to have a 60% capture efficiency, which is within the range of regular range hood and microwave range hood combinations (Zhao et al., 2020). In Suggested ventilation and Full ventilation scenarios, the range hood was always used during any types of cooking events. Unlike bathroom exhaust and dryer ventilation, the range hood was assumed to start when the cooking started and end with the cooking at the specified 100 cfm airflow. In Minimum and Continuous only ventilation scenarios, the range hood was not used. Details about the schedule and duration of cooking events are discussed in Section 2.2.4.

2.1.6.4 Window Use

Window use was simulated to investigate the impact of natural ventilation on indoor air pollutants from various origins. As described in the Section 2.3.3, one 36 by 12 inch, two-way flow element was assigned on the north and east walls to simulate cross ventilation by opening windows. The size of the opening area is comparable to other studies of small window openings or half window openings (Lo & Novoselac, 2012). The two opening areas were scheduled in CONTAM to be either fully open or fully closed. For operable window scenarios, windows were scheduled to be open during any 6-hour period with no HAC operation. This assumption represents an aggressive window opening schedule.

2.2 Air Pollutant Modeling

2.2.1 Sources of Air Pollutants

We modeled four air pollutants: $PM_{2.5}$, NO_2, Acrolein and formaldehyde. The sources of these pollutants include indoor continuous emissions, cooking emissions and outdoor infiltration. The details of the source for each pollutant are shown in Table 7. In the CONTAM model, pollutants with different sources are tracked independently. Outdoor pollution data and the emission rates (non-cooking and cooking) and loss mechanisms are discussed in detail in the subsections below.

Table 7 Summary of the pollutant sources.

Pollutant	Outdoor	Indoor continuous	Cooking
$PM_{2.5}$	x	When awake	x
NO_2	x		x
Acrolein		x	x
Formaldehyde		x	

2.2.2 Outdoor Pollutant Data

We developed hourly typical (50th percentile) outdoor pollutant data time-series for $PM_{2.5}$ and NO_2 for the three regions outlined above, using publicly available data files retrieved from the US EPA AirNow API ambient monitoring system from years 2010-2020 (https://docs.airnowapi.org/). Urban centers (like Chicago, Houston and Fresno) tend to have the majority of ambient air quality monitoring stations in a region, but there are typically low concentrations of manufactured homes in the urban center, which are more commonly located at the outskirts of an urban area (i.e., in the suburbs and even the exurbs). Furthermore, ambient concentrations may be substantially different between the urban center and suburban elements of any given region. In consideration of these factors, monitoring data was gathered from larger geographic areas of diverse land use surrounding the three urban centers, including both urban and suburban monitoring sites. These would then cover MHs distributed across the larger areas. All sites used in outdoor data processing are shown in Figure 3. Notably, each monitoring station has different amounts of data available over the 10 year period, so they are not equally weighted in the resulting ambient concentration files. In

Table 8, we show the count of observations over the 10-year period for each site and region.

With ten years of ambient air quality data broadly representing the three regions of interest, we calculated statistics for each region and hour of the year, including the median (50th) and 98th percentile pollutant concentrations, across all years and monitoring sites. The time-series median values for each location and contaminant are plotted in Figure 4. Each of the three regions were simulated using their respective median ambient pollutant profiles. In addition, the 98th percentile values in the Fresno location were used to assess the impact of higher outdoor pollutant levels during wildfire events in this region. Using the 98th percentile values from each hour of the year likely overestimates the year-round outdoor concentrations during non-wildfire season. However, the daily extremes are appropriate for wildfires and extreme-case analysis. Annual average outdoor concentrations for the median and 98th percentile profiles are tabulated for each location and pollutant in Table 9.

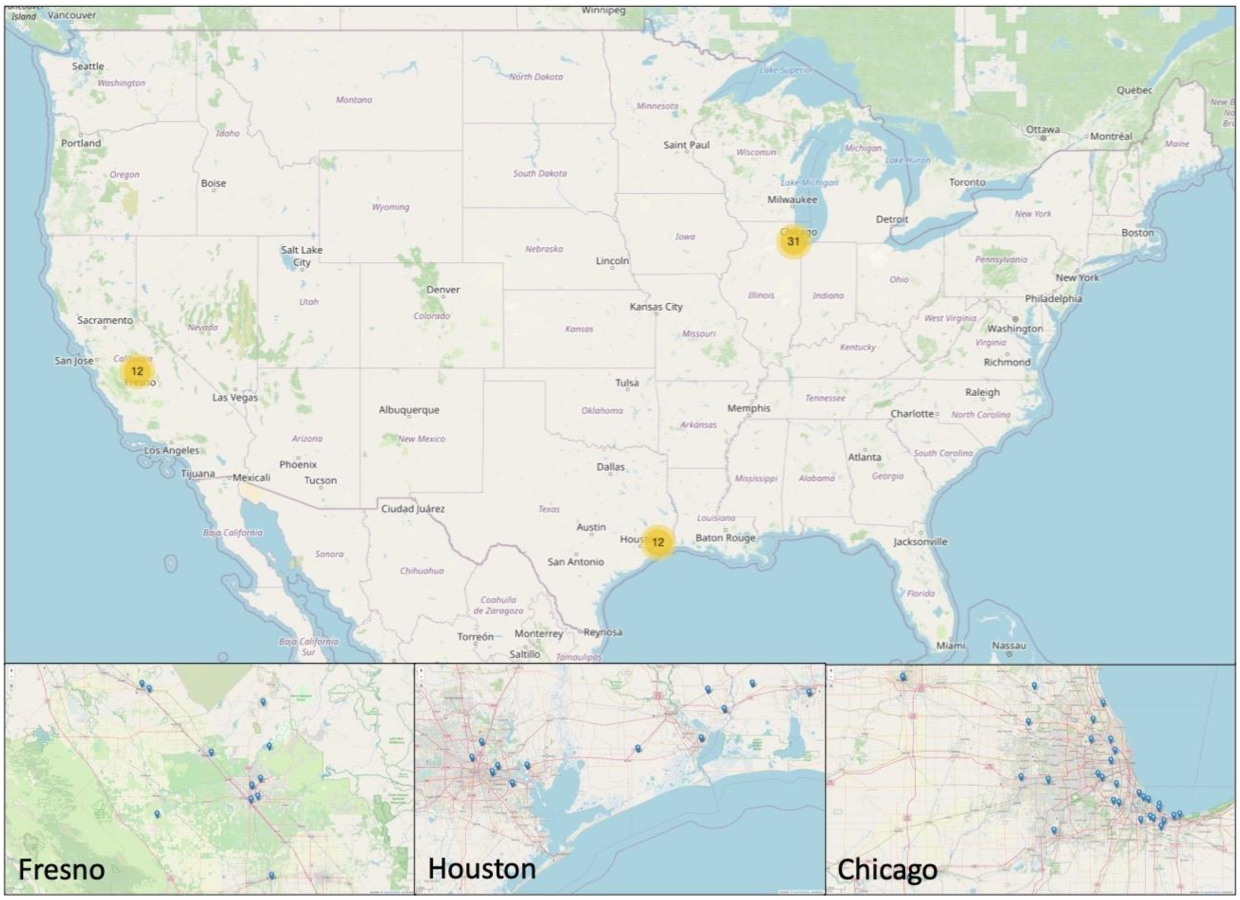

Figure 3 Map showing the count of US EPA monitoring sites located in each simulation region.

Table 8 Tabulation of US EPA monitoring sites in each simulation region, including site coordinates and number of observations.

Chicago			Fresno			Houston		
Lat	Long	Obs_n	Lat	Long	Obs_n	Lat	Long	Obs_n
41.61	-87.30	85340	36.79	-119.77	129536	29.67	-95.13	71960
42.14	-87.80	29886	37.28	-120.43	89678	29.77	-95.03	31022
41.59	-87.48	28939	36.32	-119.64	89522	29.92	-93.91	28417
42.06	-87.86	26538	36.82	-119.72	86102	30.19	-93.87	28113
41.77	-88.15	24361	36.95	-120.03	85846	29.86	-94.32	28101
41.59	-87.50	24128	36.63	-120.38	83890	29.77	-95.22	27856
41.53	-88.12	23222	36.99	-119.66	39397	29.90	-95.33	14188
41.58	-87.56	15450	37.21	-119.70	21626	29.73	-95.26	4400
42.27	-89.09	15139	36.71	-119.78	8554	30.23	-93.58	1340
41.65	-87.44	10030	36.78	-119.77	3224	29.81	-95.39	641
41.60	-87.34	1896	36.73	-119.73	1156	30.18	-93.21	610
41.57	-87.41	1532	37.31	-120.48	1149	30.09	-93.76	46
41.80	-87.83	1359						
41.64	-87.44	1258						
41.69	-87.54	1088						
41.97	-87.75	1069						
41.97	-87.88	987						
41.78	-88.33	940						
41.78	-87.81	879						
42.05	-88.28	745						
42.26	-89.09	493						
41.75	-87.71	485						
41.91	-87.72	474						
42.22	-88.24	462						
41.86	-87.75	461						
41.67	-87.73	358						
41.68	-87.51	338						
41.55	-87.43	234						
41.71	-87.57	117						
41.66	-87.70	116						
41.29	-89.05	113						

Table 9 Annual median concentrations for each contaminant, location and profile.

Pollutant	Location	Annual Mean of Hourly Medians Across Monitoring Sites	98th Percentile of Hourly Medians
PM ($\mu g/m^3$)	Chicago	9.0	
	Fresno	11.0	41.4
	Houston	8.4	
NO_2 (ppb)	Chicago	13.3	
	Fresno	8.3	26.3
	Houston	5.6	

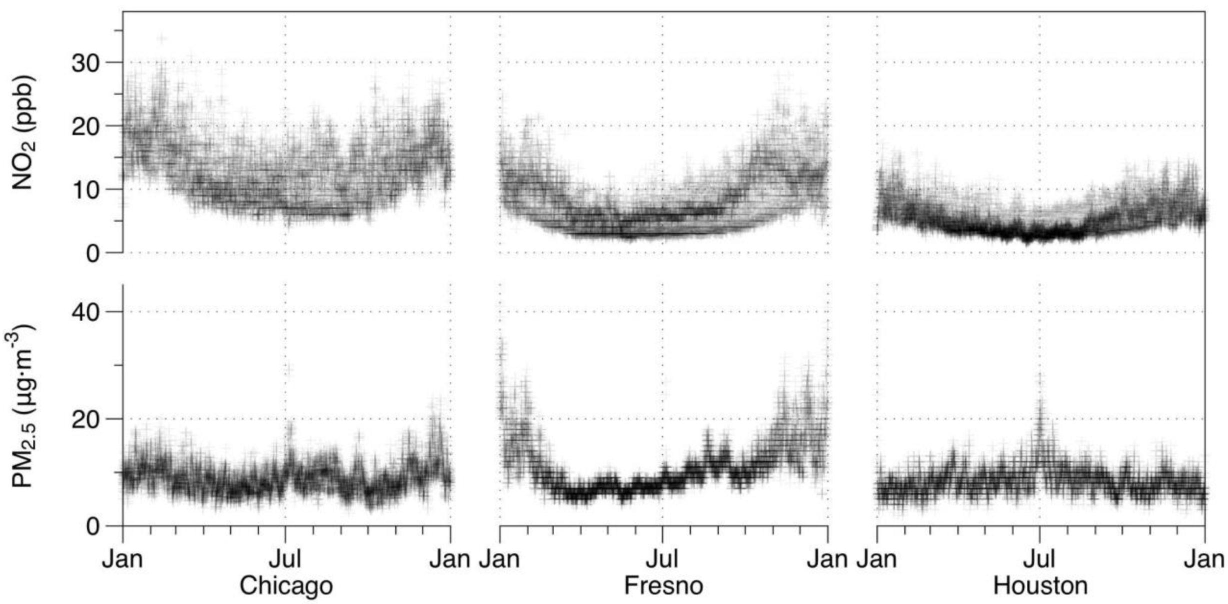

Figure 4 Time-series plots of the derived median outdoor pollutant profiles for $PM_{2.5}$ and NO_2 in each simulation location.

2.2.3 Non-Cooking Indoor Emissions

Non-cooking pollutant emissions include those for formaldehyde, acrolein and $PM_{2.5}$, which are detailed in Table 10. Formaldehyde and acrolein are emitted continuously from the building envelope and by materials in the home. These emissions are proportional to the dwelling floor area, with base emission rates expressed in $\mu g/m^2$-hr. Using the base emission rates and the standard size of the modeled double-section MF (1,568 ft^2), total emissions are expressed in Table 10 in mg/hr. $PM_{2.5}$ from occupant activities other than cooking was emitted at a constant rate when occupants were awake from 7 am to 11 pm each day. Background is provided for the emission rates selected for each of these contaminants in the subsections below.

Table 10 Summary of the building continuous emission rates of formaldehyde and acrolein, and the continuous emission rate of $PM_{2.5}$ for occupants' activities.

	Formaldehyde	***Acrolein***	$PM_{2.5}$ ***(when awake 7am to 11pm)***
Base Emission Rates	20 μg/m^2-hr	2.8 μg/m^2-hr	0.5 mg/hr
Emission Rates Used for Double Section MH Prototype (1568 ft^2)	2.9 mg/hr	0.4 mg/hr	0.5 mg/hr

2.2.3.1 Building Formaldehyde Emissions

New manufactured homes in the US are subject to strict limitations on the emissions of formaldehyde from composite wood products. As of March 2020, HUD incorporated strict formaldehyde emission control requirements for manufactured homes (Final Rule 85 FR 5562[5], 24 CFR Sections 3280 and 3282) that match those in the 2016 US EPA Final Rule implementing the Formaldehyde Standards for Composite Wood Products Act. These were modeled to exactly match requirements in Phase 2 of the California Air Resources Board's (CARB) Air Toxic Control Measure (ATCM). The regulations include emission limits by product type, incorporation of ASTM emission test methods, and requirements for product labeling and manufacturer documentation.

Consistent with these requirements to use low-formaldehyde emitting materials, we have selected a formaldehyde emission rate for MH based on measurements in other single-family detached homes using low formaldehyde emitting materials. Indoor emission rates of formaldehyde were continuous and assumed to be 20 μg/m2-hr in the analysis. This value was based on two recent studies in new California homes built with low formaldehyde emitting materials. (Hult et al., 2015a) reported a mean emission rate of 23 μg/m^2-hr in 9 new homes. The HENGH study reported mean and median emission rates of 17 and 16 μg/m^2-hr in 61 new California homes (Chan et al., 2019)(Singer et al., 2020). We acknowledge that formaldehyde emission rates have previously been shown to vary with indoor environmental conditions, such as temperature, humidity and air exchange rate (Hult et al., 2015b) but methods do not readily exist to accurately include these influences in simplified modeling efforts. Ambient formaldehyde concentrations were treated as 0 in our modeling.

2.2.3.2 Building Acrolein Emissions

Acrolein is treated as having only indoor sources, as they have been shown to very strongly dominate outdoor sources. Continuous acrolein emissions indoors are from building materials (lumber) and furnishings, with secondary emissions from oxidation of other indoor VOCs. A study reported morning and evening acrolein measurements in 9 California homes, as well as in unoccupied and new model homes (Seaman et al., 2007, 2009). All homes showed strong diurnal acrolein patterns, with evening concentrations higher than those in the morning, by as much as 2.5x. These increases were associated with increased indoor temperatures and with cooking. In this study, we use the average value of 2.8 μg/m^2-hr measured in the morning in the 9 California homes. We take this as the building-related emissions, assuming these measurements excluded contributions from cooking.

2.2.3.3 $PM_{2.5}$ Emissions from Occupants' Daily Activities

Continuous $PM_{2.5}$ emissions from human daily activity were calculated using a data set consisting of measurements from 70 single-family houses and 23 low-income apartments built from 2011 to 2017 in California. In this dataset, the indoor PM emission events were first identified by applying a machine learning approach to the time-resolved PM concentrations measured in each home (Tang et al., 2021;

[5] https://www.govinfo.gov/content/pkg/FR-2020-01-31/pdf/2020-01474.pdf

Zhao et al., 2020). That resulted in 5114 mg total PM mass emitted from 53 measured single family houses and 2825 mg total PM mass emitted from 20 low-income apartments. Then the PM emission events were linked with cooking burner use, which was identified by the temperature data for each individual burner. We found 66% of the PM mass emitted was cooking-related in single-family houses and 19% was cooking-related in low-income apartments. Finally, the average non-cooking related $PM_{2.5}$ emission rate during daily activity was calculated using the total non-cooking related PM mass in 73 homes normalized by the total monitoring duration. We assumed a daily active time period from 7am to 11pm, resulting in an average emission rate of 0.52 mg/hr during the active period. The value is lower than the one found in an older study from 1996 (Wallace, 1996), which estimated an average non-cooking and non-smoking source of 1.1 mg/h.

$PM_{2.5}$ from human daily activities should vary with occupancy hours. To verify this, the total non-cooking PM mass emitted from each home were compared to the total occupancy hours (number of occupants*hour) between 7am to 11pm based on households' self-reported occupancy. Results show no obvious relationship between non-cooking PM mass in homes and occupancy hours based on both Spearman rank and Pearson rank correlations. Thus, an average emission rate of 0.52 mg/hr was used for each home between 7am to 11pm, regardless of the occupancy at each residence.

2.2.4 Cooking Indoor Emissions

The weekly schedule of emissions for $PM_{2.5}$, NO_2 and acrolein from cooking are shown in Table 11. Cooking indoor emissions are assembled from a cooking schedule for each day of a typical week, combined with emission rates for each scheduled meal type and time of day. The schedules are described below in Section 2.2.4.1, followed by emissions data for each scheduled cooking activity and contaminant described in Section 2.2.4.2.

Table 11 Pollutant emission rates from cooking on a weekly schedule.

Meals	**Pollutant emission**	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Breakfast 8:00-8:15	$PM_{2.5}$ (mg/min)		4		4		4	4
	NO_2 (mg/min)		1.7		1.7		1.7	1.7
	Acrolein (mg/min)		0.21		0.21		0.21	0.21
Lunch 12:00-12:20	$PM_{2.5}$ (mg/min)		0.35	2	0.85			
	NO_2 (mg/min)		1.7	1.7	3.2			
	Acrolein (mg/min)			0.21				
Dinner 18:00-18:30	$PM_{2.5}$ (mg/min)	0.47	3	2	0.47	4.4	4.4	2.2
	NO_2 (mg/min)	3.4	3.4	3.4	3.4	6.6	6.6	6.6
	Acrolein (mg/min)		0.43	0.43		0.43	0.43	

2.2.4.1 Cooking schedule background

We developed weekly cooking schedules with high cooking frequency per week based on data reported in the research literature. (Klug et al., 2011) reported questionnaire data on weekly cooktop and oven use frequency from 372 homes, showing that median cooktop use is 1-2 days per week for breakfast, 1-2 days for lunch and 4-5 days for dinner. The median oven use is 0 per week for breakfast, 0 for lunch and 1-2 days for dinner. We also analyzed the measured cooktop burner and oven use in 70 new California single-family homes (Chan et al., 2019). In 57 homes with cooktop burner use detected over a period of 376 days, usage events were recorded for breakfast (212 events (56% of days)), lunch (93 (25%)) and dinner (280 (74%)). That translates to cooktop burner use 3.9 times per week for breakfast, 1.7 times per week for lunch and 5.2 times per week for dinner. 24 oven use events (6%) were recorded for breakfast, 24 (6%) for lunch and 101 (27%) for dinner. This translates to oven use 1.9 times per week for dinner, with almost no oven use for lunch and breakfast. In a recent study in 132 Canadian households (Sun & Wallace, 2020) also surveyed cooking frequency at each mealtime, and in 1,848 survey days, 952 meals were cooked for breakfast, 658 for lunch and 1,138 for dinner. That translates to 3.6 breakfast events, 2.5 lunch events and 4.3 dinner events per week.

Based on the summaries provided above, an average cooking frequency would be cooktop burner use 4 breakfasts, 2 lunches and 5 dinners per week, with the oven use twice a week during dinner, together with dinner on weekends. We used a more frequent cooking schedule in this study to simulate a household with lots of cooking activity. We assumed cooktop burner use for 7 breakfasts, 5 lunches and 7 dinners per week, which is consistent with the 90th percentile from the survey in Klug 2011. The oven was used three times a week during dinner, together with cooktop use on weekends and Friday.

Cooking duration and cooking methods. The cook time or the minutes of burner use reported or measured in the three studies mentioned above are shown in Table 12. Overall, the estimated cook times are 5-15 minutes for breakfast, 15-20 minutes for lunch and 20-30 minutes for dinner. For dinner with both cooktop and oven use, we assume they were used at the same time. Based on these ranges, we assumed 15 minutes of cooking time for breakfast, 20 minutes for lunch and 30 minutes for dinner.

Table 12 Summary of cooking time by meal in previous studies.

Burner	**Cooking Time**	**GM**	**GSD**	**n**	**Study and data type**
Cooktop	Breakfast	10.8	1.5	163	Klug et al. 2011. Self-report cooktop and oven use minutes
	Lunch	14.6	1.9	77	
	Dinner	26.9	1.6	257	
Oven	Breakfast	15.1	1.8	25	
	Lunch	14.4	1.8	16	
	Dinner	37.7	1.7	138	
Cooktop	Breakfast	14.58	2.23	212	HENGH Field Study Chan et al. 2019. Measured burner-minutes
	Lunch	18.65	2.34	93	
	Dinner	20.89	2.35	280	
	Other	14.06	2.3	82	
Oven	Breakfast	27.12	3.28	24	
	Lunch	28.81	2.13	24	
	Dinner	31.16	2.24	101	
	Other	38.36	2.38	17	
Any	Breakfast	5.4	2.7	952	Sun and Wallace 2020. Self-report cooking minutes
	Lunch	13	3.1	658	
	Dinner	18	2.5	1138	

We also assigned different cooking methods based on the frequency of methods used for each mealtime in the literature. Sun and Wallace 2020 report cooking methods and devices in detail by mealtime in

Figure S1 of their paper (reproduced with permission in Figure 5). For example, the most frequent methods for breakfast were toaster toasting and stove frying. We assigned frying for 4 breakfasts on Tuesday, Thursday, Saturday and Sunday, and other breakfast would be toaster toasting. We tried to avoid the same cooking methods for adjacent meals on the same day. A fully elaborated cooking schedule for a high cooking frequency is shown in Table 13.

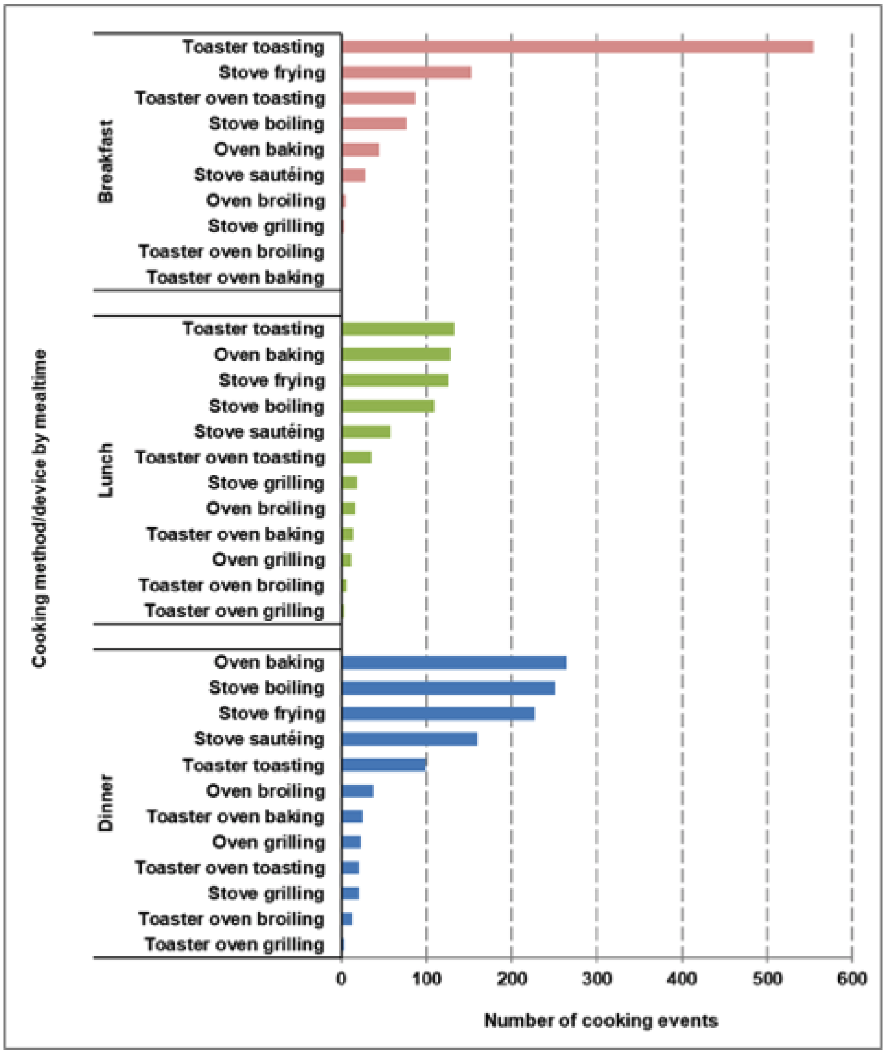

Figure 5 Cooking method by mealtime reported by Sun & Wallace, 2020.

Table 13 Weekly cooking schedule for high-frequency cooking.

Meal	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Breakfast 8:00-8:15	Toaster toasting	Stove frying (P,N,A)	Toaster toasting	Stove frying (P,N,A)	Toaster toasting	Stove frying (P,N,A)	Stove frying (P,N,A)
Lunch 12:00-12:20		Stove boiling (P,N)	Stove frying (P,N,A)	Oven baking (P,N,A)		Toaster toasting	Toaster toasting
Dinner 18:00-18:30	stove boiling (P,N)	stove frying (P,N,A)	Stove Sautering (P,N,A)	stove boiling (P,N)	Oven baking + stove frying (P,N,A)	Oven baking + stove frying (P,N,A)	Oven baking + stove boiling (P,N,A)

Pollutants emitted from each meal were labeled: P=$PM_{2.5}$, N=NO_2, A=Acrolein

2.2.4.2 Cooking emissions background

We also considered different pollutant emissions for different cooking methods. A summary of the durations, total emissions and emission rates for each cooking method and contaminant by mealtime are shown in Table 14. Background on the cooking emission rates for each contaminant are provided in subsections below.

Table 14 Pollutant emission rates by mealtime and cooking method.

Meal (mass food cooked per person)	Activity	PM mass per event (mg)	Event duration (min)	PM emission rate (mg/min)	NO_2 emission rate (mg/min)	Acrolein emission rate (mg/min)
Breakfast: 250 g/per	Stove frying Bacon	60	15	4	1.7	0.21
	Toaster toasting	0	15	0	0	0
Lunch: 250 g/per	Toaster toasting	0	5	0	0	0
	Stove frying	40	20	2	1.7	0.21
	Stove boiling	7	20	0.35	1.7	0
	Oven baking	17	20	0.85	3.2	0.1
Dinner: 500 g/per stovetop; 1000 g/per when using oven (500 g) + stovetop (500 g)	Stove sauteing	60	30	2	3.4	0.43
	Stove frying	80	30	2.7	3.4	0.43
	Stove boiling	14	30	0.47	3.4	0
	Oven baking + stove frying	130	30[1]	1.7+2.7	3.4+3.2	0.43
	Oven baking + stove boiling	62	30[1]	1.7+0.47	3.4+3.2	0

[1] 30 min cooktop + 30 min oven overlapping

2.2.4.2.1 Cooking PM emissions

The mass of food cooked for each meal type is based on the number of occupants. The EPA Exposure Factors handbook suggests that on average people consume around 1 kg of food per day (roughly consistent from age 2 to elderly) (US EPA National Center for Environmental Assessment, 2011). Our analysis assumes half of this intake is at dinner (0.5 kg), and the other half is evenly split between breakfast (0.25 kg) and lunch mealtimes (0.25 kg). For dinner cooked with both the cooktop burners and the oven on Friday and weekends, we assumed an additional 1 kg of food cooked, split evenly between cooktop burners and the oven.

For breakfast, toaster toasting was considered to have no PM emissions. Stove frying was considered to be frying bacon and eggs with an emission rate of 4 mg per minute. The $PM_{2.5}$ emission rate for stove frying was estimated to be 137 µg/g of food, based on measured emissions when stove frying roughly 0.7 kg food in 21 min (Fortmann et al., 2001).

For lunch, cooking emissions included a fried chicken meal, boiling water and oven baking. The total emissions of $PM_{2.5}$ for a fried chicken meal with 0.6 kg to 0.8 kg food varied from 20 mg to 50 mg per meal in previous studies (Fortmann et al., 2001; O'Leary et al., 2019). Here we used 45 mg of $PM_{2.5}$ emissions per meal for a 3-person lunch. Few particles are emitted from a boiling event. Sun and Wallace reported a geometric mean emission rate of 0.35 mg/min in boiling events with an average duration of 15 minutes. Here, we use 0.35 mg/min emission rate with a 7 mg total emitted mass for a 3-person lunch. $PM_{2.5}$ emissions from oven baking varied widely in previous studies. Fortmann et al. found baking 1.1 kg frozen lasagna emitted about 180-500 mg PM during a two-hour baking time. Sun and Wallace found the value to be 3.8-159 mg, with an average baking time of 41 minutes. We use the geometric mean of the total emissions (17 mg) found from the latter study, because the baking time is close to our assumption for lunch cooking (20min). An emission rate of 0.85 mg/min was used for baking 20 minutes for a 3-person lunch.

For dinner, we assume the mass of food cooked was doubled for dinner cooked with only the cooktop, and mass of food cooked was quadrupled for dinner cooked with both the cooktop and an oven. Thus, the emission rate for a certain cooking method would be doubled for dinner compared to lunch, assuming only cooktop use. For a dinner that uses both the cooktop and oven, we assume that they were used at the same time for a 30 min period, 0.5 kg of food per person were cooked on the cooktop and 0.5 kg of food per person were cooked using the oven. The emission rate of stove sauteing was assumed to be 60 mg total emission at 2 mg/min in 30 minutes of cooking time for a 3-person lunch.

2.2.4.2.2 Cooking NO_2 emissions

Measurements of NO_2 emissions from gas cooking events were performed in nine homes in California (Singer et al., 2017), and the median emission rate was 10 ng/J, ranging from 5-15 ng/J. The average power consumption for a cooktop burner was 10 kBtu/hr and most of the gas ovens in the test homes were 18 kBtu/hr. That results in a NO_2 emission rate of 1.7 mg/min per cooktop burner and 3.2 mg/min per oven. For comparison, Fortmann et al. reported NO_2 emissions from a variety of scripted gas cooking activities, and they fell between 26 and 168 mg/hr (0.4-2.8 mg/min). (Klug et al., 2011) surveyed 372 homes and found most of the homes use 2 cooktop burners or less for cooking (based on Figure 3 in Klug et al. 2011), and almost half of the dinner events included 2 cooktop burners. Thus, for breakfast and lunch, we assumed one cooktop burner was used (1.7 mg/min) and for dinner two cooktops burners were used (3.4 mg/min). For dinners with oven use, we assumed that two cooktop burners and the oven were used at the same time (3.4+3.2 mg/min).

2.2.4.2.3 Cooking acrolein emissions

The cooking acrolein emission rate is based on a lab study that measured the acrolein emissions for various cooking activities with different types of oil (Seaman et al., 2007). We used the average emission rate of 17 mg/hr-kg food (0.28 mg/min-kg food) in this modeling study. We assumed that acrolein emission occurs only when cooking with oil such as frying and sauteing. The acrolein emission rates were then normalized by the amount of food cooked per meal.

2.2.5 Indoor Pollutant Loss Mechanisms

In the CONTAM modeling, all pollutants are transported by ventilation with outside air, but additional loss mechanisms include those associated with envelope penetration, deposition and filtration. Table 15 lists the relevant parameters for each loss mechanism and pollutant species. Penetration Factor refers to the fraction of an ambient pollutant that enters a building with infiltrating outdoor air. A penetration factor of 0.9 means that 10% of the pollutants coming from outdoors are removed during infiltration. Indoor deposition/losses include deposition on surfaces, or agglomeration with other particles, as well as surface reactions. Filtration efficiency represents the percentage of particles removed from the air stream passing through the HVAC filter. The justifications and reference values for each of these loss mechanisms are described in the following subsections addressing each individual pollutant. Formaldehyde is assumed to be non-reactive, to have no outdoor source and with no removal mechanisms other than air exchange. Acrolein deposition is extremely low, estimated to be 0.04/hr (Seaman et al., 2009).

Table 15 Summary of the loss parameters for each pollutant.

Pollutant	**Penetration Factor (p)**	**Indoor Deposition/Loss (k, hr^{-1})**	**Filtration Efficiency**
$PM_{2.5}$	0.8	0.7	10%
NO_2	1	0.75	0%
Acrolein	1	0.04	0%
Formaldehyde	NA	0	0%

2.2.5.1 $PM_{2.5}$

The $PM_{2.5}$ deposition rate used a value of 0.7/hr. This is based on analysis of the $PM_{2.5}$ time series in 58 Canadian homes during both winter and summer (Wallace et al., 2013). Wallace et al. reported median deposition rates of 0.60/h with an interquartile range of 0.37 to 1.3/h. These deposition rates are higher than the point estimate of 0.3/h used in a modeling system developed for estimating $PM_{2.5}$ and other pollutants in large populations of US homes (Fazli & Stephens, 2018), and they are lower than the $PM_{2.5}$ deposition rates inferred from size-dependent rates reported for a study of cooking-related PM emission events in 14 houses in Australia (He et al., 2004).

We assume the $PM_{2.5}$ penetration factor to be 0.8 based on several studies in the literature. (Long et al., 2001) analyzed time- and size-resolved PM data to estimate a range for penetration factors of 0.2 to 0.9 in 9 homes. (Wallace & Williams, 2005) estimated a penetration factor for $PM_{2.5}$ of 0.72 (standard deviation = 0.21) in 37 NC homes. In 212 homes in the RIOPA study, the $PM_{2.5}$ penetration factor was estimated to be 0.91 based on gravimetric mass samples (Meng et al., 2005). In a recent modeling study, a $PM_{2.5}$ penetration factor of 0.82 was estimated by combining size-resolved penetration factors in the lab and ambient $PM_{2.5}$ concentration distributions (Fazli & Stephens, 2018).

We performed simulations assuming that indoor $PM_{2.5}$ mass is removed by a 10% efficient filter located in the central, forced air HAC system. The filter was assumed to be placed at the recirculating fan, so both outside air from the CFIS intake and recirculated air from the conditioned space were filtered. Particles are only removed during fan operation. The 10% removal efficiency is consistent with the minimum filter performance requirements in the ASHRAE 62.2-2016 ventilation standard (MERV 8), as well as with the low-end range of typical $PM_{2.5}$ removal recently documented from a wide variety of commercially available residential filters (Fazli et al., 2019).

2.2.5.2 NO_2

Loss of NO_2 indoors is caused by deposition and reaction with surfaces. For the current analysis, we pick a central estimate of 0.75/hr. In a prior LBNL study that estimated exposures to NO_2 from natural gas cooking burners, NO_2 first-order deposition loss rates were modeled as being either 0.5/h or 1.05/h (Logue et al., 2013). These span the range of values between 0.11 and 1.4/h reported in literature for furnished residences (Nazaroff & Cass, 1986; Noris et al., 2013; Spicer et al., 1993; Yang et al., 2004). Differences in NO_2 loss rate can be partly explained by humidity effects and variations in indoor surface characteristics. Similar NO_2 loss rates were found by (Zhou et al., 2018) in a single-family NY house, and also in 17 Illinois homes (Francisco et al., 2010) and (Gordon et al., 2008).

We assume an NO_2 penetration factor of 1.0, with no losses associated with incoming air passing through the building envelope or duct inlets. Recently, an NO_2 penetration factor of 0.72 (standard deviation = 0.06) was reported for an unoccupied, sparsely furnished apartment in Illinois (Zhao et al., 2019). However, the applicability of that value to single-family residential analysis is questionable, due to differences in the flow paths of incoming air.

2.3 Simulation Framework

Each of the simulation tools used have unique benefits and constraints, but when combined together, the quality of the results are improved. Our workflow was designed to leverage the respective strengths of each tool. We used the CONTAM multizone airflow and indoor air quality model (ver3.4.0.1, National Institute of Standard Technology) for hourly predictions of outside airflow rates and indoor pollutant concentrations. EnergyPlus (v8.4) was used to predict the hourly building thermal balance, indoor temperatures and mechanical system operation. A process diagram of the modeling framework is shown in Figure 6.

The modeling process included the following three steps, each of which are described in additional detail in subsections below:

1. EnergyPlus simulation of thermal loads, HAC runtime and indoor temperatures. Inputs include building geometry, weather data, thermal characteristics and occupancy schedules.
2. Post-processing adjustment of EnergyPlus HAC system airflow and runtime outputs based on equipment sizing, energy losses related to duct leakage and central fan integrated supply (CFIS) airflow.
3. CONTAM simulation of airflow and contaminant transport, using identical building geometry and weather data, along with adjusted schedules from EnergyPlus.

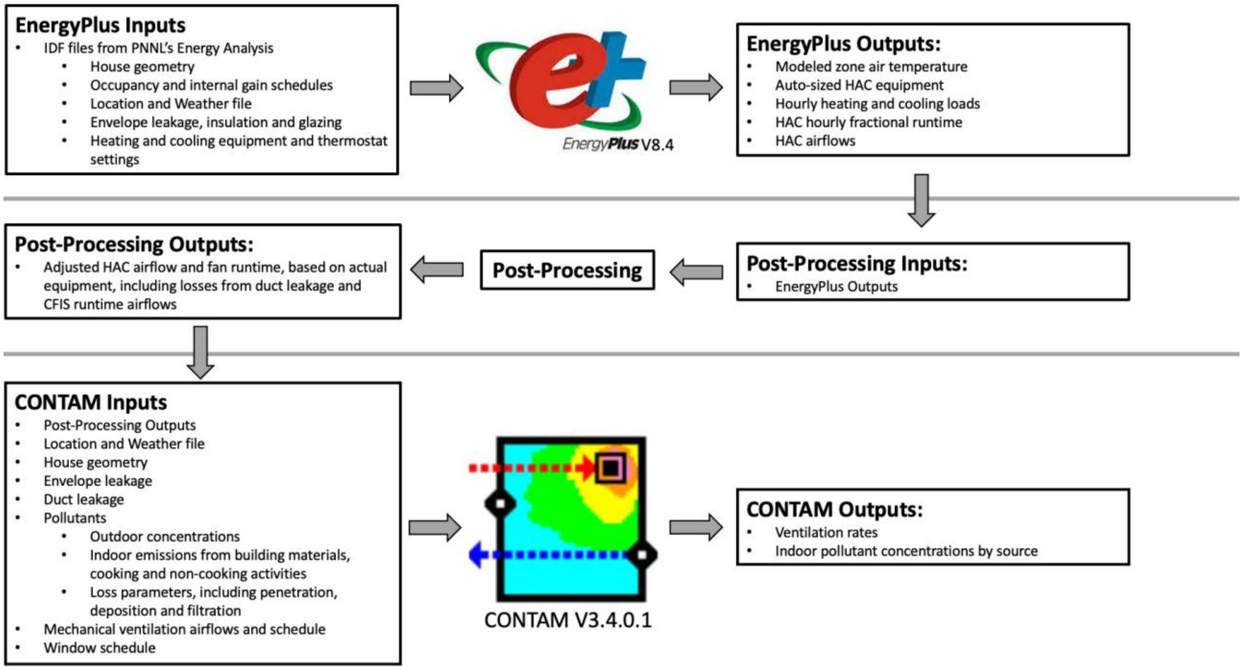

Figure 6 Process diagram of the modeling framework.

2.3.1 EnergyPlus Modeling

The role of EnergyPlus in this framework was to generate indoor dry bulb temperatures, HAC equipment sizing, airflow and runtime data, which are essential inputs to the CONTAM models. Indoor temperatures are used in CONTAM to determine outside air exchange resulting from differences in indoor and outdoor temperature. The HAC equipment specifications and operation are used in CONTAM to determine the volume and timing of air duct leakage and CFIS induced air exchange and particle removal from filtration of the central air handler.

EnergyPlus input files used in our analysis were originally created by Pacific Northwest National Laboratory (PNNL) in their analysis of the energy impacts of the proposed rule. The details of the PNNL models are documented in the Technical Support Document (TSD) for the proposed DOE rule (US DOE, 2021). PNNL created two versions of its models: one version incorporating EnergyPlus airflow network models, and a second version that used simplified ventilation modeling objects. We used the simplified models, because they included the thermal loads associate with exhaust ventilation fans, and our work was designed to leverage the greater modeling capabilities of CONTAM for flow network calculations. The PNNL models included thermal envelope characteristics that meet the current HUD code and the proposed rule in a variety of climate zones (tiers 1 and 2). The provided models also included a suite of heating and air conditioning systems that satisfy HUD code requirements or those of the proposed rule. From amongst the candidate models shared by PNNL, we selected those with thermal envelope parameters that align with the current HUD code and with the Tier 2 requirements in the proposed rule (see Table 6.6 of the TSD). We used the models with either a heat pump, or a combination of air conditioning and natural gas furnace.

We made a number of changes to the EnergyPlus input files shared by the PNNL team. First, we adjusted thermostat setpoints to align with those observed in field studies across the relevant locations (see Table 1). Second, we changed the envelope leakage object stack and wind pressure coefficients to use 1-story coefficients from the ASHRAE Handbook of Fundamentals, rather than 2-story coefficients, as were originally implemented in the PNNL models. This change is expected to reduce outside natural infiltration airflows and lower estimated heating and cooling loads. We implemented an example simulation in Houston to compare the envelope leakage coefficients, and HAC runtime was reduced by roughly 5% when using the 1-story coefficients. Third, for modeling CFIS ventilation system types, we removed the exhaust fan objects from the EnergyPlus files, and instead estimated mechanical ventilation loads for runtime CFIS systems in post-processing (see Section 2.3.2). Finally, we adjusted the leakage coefficients used in the EnergyPlus attic zone models to more closely reflect the air exchange dynamics of residential vented attics.

In total, 24 EnergyPlus models were run using a 15-minute timestep and one-hour reporting interval, including cases with and without whole dwelling exhaust fan objects, with two HAC types, two envelope insulation and leakage levels (HUD code and Tier 2 of the Proposed Rule) and three climate zones. The default 3-person occupancy pattern from the PNNL models was used in the EnergyPlus models, but later CONTAM modeling adjusted occupancy to be continuous. Weather data for each location was read from relevant typical meteorological year (TMY3) files. We used the auto-size feature in Energy Plus, where heating and cooling equipment capacities (P_{E+}) and airflow rates are automatically selected based on design day runs of the model. We also assumed low-cost central HAC equipment, with the same airflow for both heating and cooling modes. The HAC fan speed was treated as constant over time. The EnergyPlus simulations ignored local exhaust fans in the kitchen and bathrooms, duct leakage and CFIS ventilation airflow impacts on heating and cooling loads.

EnergyPlus outputs were recorded (and in some cases adjusted) to be used in the CONTAM model runs, including conditioned zone indoor air dry-bulb temperature, hourly heating and cooling load for the conditioned living zone, auto-sized HAC airflow, capacity and hourly fractional runtime. Adjustments to these outputs are discussed in the following section.

2.3.2 Adjustment of EnergyPlus Runtime and Airflow

We adjusted the central HAC fan airflows to align with actual equipment and configurations commonly used in MH. Using the auto-sized cooling and heating equipment capacities, we identified best matches with actual equipment listed by Miller Heating and Cooling. This company is known as a common equipment provider for the US MH market. For furnaces and air conditioning units, we selected actual products with the lowest capacity that exceeded the design loads from EnergyPlus (cooling loads were used to select heat pump equipment). If the selected equipment had multiple airflow settings, we chose the lowest airflows recommended by the manufacturer to meet the cooling and heating loads (including CFIS flows in Fresno, medium-low, see additional details in Section 2.1.5). In cases with both a furnace and air conditioning, if the required airflows of the two devices were different, the larger airflow was used as the fixed central air handler flow.

The selected equipment, capacities and airflows for each location under current HUD rules and the proposed rules are detailed in Section 2.1.5. The equipment sizing factor (E_f) is defined as the ratio of Energy Plus auto-sized heating and cooling capacity to the capacity of the nearest available unit in the market that exceeds the required load, as shown in Equation 1.

$$E_f = \frac{P_{E+}}{P_{equip}} \quad (1)$$

Duct leakage and the CFIS airflow were not included in the Energy Plus thermal modeling, so the auto-sized cooling and heating loads represent only the thermal energy required in the conditioned zone (Q_{req}). The required zone loads (Q_{req}) can be represented as the product of the modeled runtime (RT_{E+}) and the modeled equipment capacity (P_{E+}) at each time-step. These required zone loads are assumed to remain fixed, irrespective of duct losses or CFIS system airflows, but the actual equipment capacity (P_a) and actual runtimes (RT_a) are expected to change. Actual system runtimes and capacities are derived for different scenarios of duct leakage and CFIS airflow by assuming these mechanisms can be treated as direct losses to equipment capacity. The hourly actual values are input to the CONTAM models, so that impacts of outside air ventilation and filtration can be accurately differentiated by duct leakage and CFIS operation.

The assumed equivalence between required zone load, modeled capacity and runtime (denoted by the "$_{E+}$" subscript), and actual capacity and runtime (denoted by the "$_{a}$" subscript) are represented in Equation 2.

$$Q_{req} = P_{E+} * RT_{E+} = P_a * RT_a \qquad (2)$$

Heat exchange associated with duct leakage and CFIS airflows are estimated using load correction factors, which are used to estimate the actual equipment capacity from the modeled equipment capacity.

Equation 3 shows the load correction factor for duct leakage (D_L) set to one minus the ratio of duct leakage airflow (F_{leak}) divided by total airflow of the air handler unit (F_a). This calculation assumes the energy loss due to duct leakage on the supply side (D_L) is a constant fraction of the total energy modeled in the supply air stream.

$$D_L = 1 - \frac{F_{leak}}{F_a} \qquad (3)$$

Equation 4 shows the load correction factor for CFIS airflow (V_L) as one minus the ratio of the CFIS load divided by the equipment capacity. The CFIS load is estimated based on the need to condition the portion of the system airflow that is drawn from the ambient environment (intake from the CFIS hole) instead of room return air. This heat transfer is calculated using the mass of the ambient air intake from the CFIS hole in kilograms per hour (m) multiplied by the enthalpy difference between return and ambient air (ΔH), calculated from weather data and Energy Plus output.

$$V_L = 1 - \frac{m * \triangle H}{P_{equip}} \qquad (4)$$

The actual hourly fractional runtime (RT_a) input to the CONTAM model was calculated using equations 1 through 4, as shown in Equation 5. This actual runtime fraction includes the impacts of specifying actual HAC equipment, including heat exchange associated with both duct leakage and CFIS airflows. The actual runtime fractions were limited to no more than 100%.

$$RT_a = \frac{E_f}{V_L * D_L} RT_{E+} \qquad \text{if } RT_a < 1$$

$$RT_a = 1 \qquad \text{if } RT_a > 1 \qquad (5)$$

2.3.3 CONTAM Modeling

CONTAM was used to estimate time-varying air exchange rates for the whole dwelling, including natural infiltration of outside air through leaks in the building envelope, mechanical ventilation and unintentional duct leakage. Air pollutant concentrations in the occupied zone were calculated in CONTAM by taking into account indoor emissions, outdoor concentrations, calculated infiltration rates, and removal by ventilation and other indoor loss mechanisms, including deposition, penetration losses and filtration. The CONTAM models were run at a 30-second time-step with hourly reporting of outputs.

A single, well-mixed zone was used to represent the occupied volume of the house, with additional zones designated to represent the supply and return sides of the HAC system, as shown in Figure 7. No attic or foundation zones were explicitly modeled in CONTAM. Modeling the complex thermal dynamics and pressure interactions of adjacent attic and foundation spaces was beyond the scope of this modeling exercise. Purpose-built models are required to appropriately reflect the dynamics between houses and attached spaces, like vented attics (Walker et al., 2005). The primary living zone was set to have a floor area of 1,568 ft^2 (145.67 m^2) and ceiling height of 7.5 ft (2.29 m), representing the most common double section manufactured homes in the US (see further details in Section 2.1.2). The floor of the MH was set at a height of 3.3 ft (1 meter) above grade.

The envelope leakage area of the whole dwelling was split between floor, wall and ceiling leakage sites. 25% of total envelope leakage was placed in the ceiling, 25% in the floor, and the remaining 50% was evenly distributed to each of the four exterior walls of the home, with each wall surface including three equal sized leakage elements aligned vertically at 0.1m (0.33 ft), 1.14m (3.75 ft) and 2.19m (7.17 ft) above the reference floor height. All above grade wall leaks used default wind pressure coefficients from CONTAM suitable for low-rise buildings, which are derived from (M.V. Swami & S. Chandra, 1987). Wind pressure coefficients for the floor leaks were set to -0.2 and ceiling leaks were -0.4, which were selected to mimic the impacts of foundation and attic spaces on infiltration flows. We used a wind speed multiplier of 0.36, representative of urban wind sheltering.

Other elements in the exterior wall surfaces include two bathroom exhaust fans, a kitchen range hood, and a vented clothes dryer (operated based on the schedules discussed in the Section 2.1.6). Two openings were located on the north and east wall to simulate two window openings (0.9*0.3 m). The temperature of the main zone in CONTAM was set to equal the zone mean air dry-bulb temperature output from EnergyPlus.

The CONTAM mass balance solved for all flows including infiltration, purposeful ventilation and duct leakage. Infiltration air flows are determined by the size and location of building envelope leaks, as well as by the driving forces affecting those leakage sites. Driving forces included buoyancy effects due to differences in indoor and outdoor temperature, as well as wind-driven flows. Purposeful mechanical ventilation included whole dwelling dilution ventilation systems, as well as intermittently operated local exhaust fans in the kitchen and bathrooms, along with a vented clothes dryer. When the HAC system operated, any duct leakage contributed directly to the outside air ventilation rate of the dwelling. Duct leaks were specified according to the conditioned floor area (e.g., 5 cfm per 100 ft^2), based on data collected from existing MH and projections of airtightness under the proposed rule. Leakage sites in the ducts were not included in the natural infiltration flows described above.

Pollutants were independently tracked by source, including continuous sources for formaldehyde and acrolein, outdoor $PM_{2.5}$ and NO_2, constant $PM_{2.5}$ emissions from human daily activity during waking hours, and cooking-related sources for $PM_{2.5}$, NO_2 and acrolein. The cooking-related sources were also specified by meal, cooking type, cooking frequencies and occupancy for $PM_{2.5}$, NO_2 and acrolein separately, which are discussed in Section 2.2.

In addition to the main conditioned zone, the HAC supply and return were each designated as a zone. Both zones were 0.93 m^3 to ensure they had minimal influence on the main zone. Each HAC zone included an orifice to outside and an orifice to the main living zone to simulate the duct opening. The two HAC zones were connected by a central air handler fan with a total flow rate that was scheduled with the HAC operation schedule derived from EnergyPlus and post-processed as in Section 2.3.2. The air handler was assigned with a particle filter for the total flows. We manually adjusted the orifice areas of the return HAC zone to achieve the desired CFIS intake airflow for each simulation. Additional details on equipment selection, fan airflow selection and CFIS adjustments can be found in Section 2.1.5. We also adjusted the orifice areas of the supply HAC zone to achieve the desired duct leakage to outside. We only considered duct leakage open to ambient air, ignoring leakage in the conditioned space or belly of the MH. This is a substantial simplification of the dynamics that are anticipated to occur in the belly area of a manufactured home, where ducts are commonly located within the road barrier and insulation layers. The thermal dynamics of the belly area are complex—and often change over time. For our modeling of pollutant concentrations in the main zone, we have focused on the air exchange between the conditioned living zone and outside. The complex interaction between main zone, belly area and duct work is not included in the scope of these simulations.

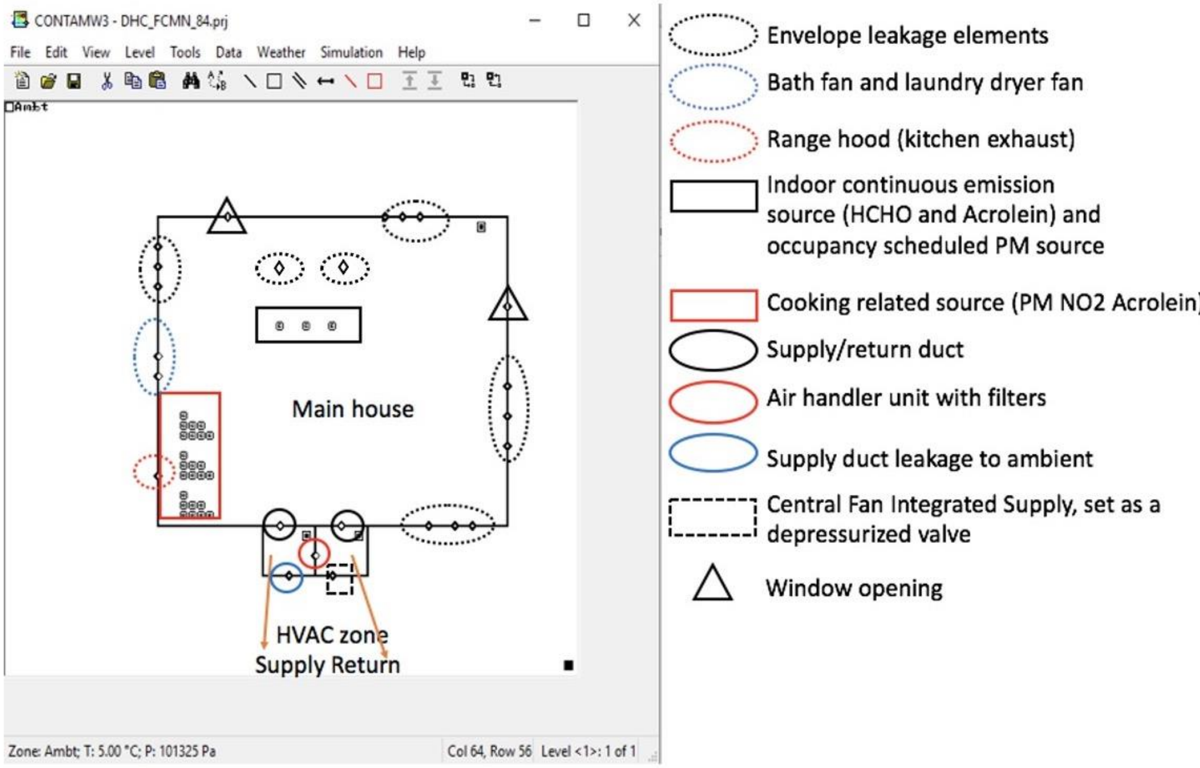

Figure 7 Schematic of the manufactured house prototype CONTAM model.

3 Results

The following subsections present the results of the simulations conducted for the specified equipment and ventilation use scenarios in the three studied locations. The key results are the calculated concentrations of pollutants from each of the individual sources (e.g., $PM_{2.5}$ originated from outdoors, from cooking or from other occupant activities), along with totals for the four specific pollutants of high concern ($PM_{2.5}$, NO_2, formaldehyde and acrolein). In considering the presented results, it is important to remember that absolute levels indoors will vary with house-specific emission rates and location-specific outdoor pollutant concentrations. The presented relative differences across ventilation configurations and with air tightness improvements are more generalizable than the specific concentrations. Also included are plots showing the calculated outside air exchange rates under all of the scenarios. For air pollutants, results are provided for an average day and for a 95th percentile highest day. For air exchange, results are presented for the average and 5th percentile lowest ventilation day.

3.1 Air Exchange Rates

An example of how outdoor air exchange rates are impacted by outdoor conditions and air leakage are shown in Figure 8, which shows the daily average AER for a home in Chicago that has either HUD Code or DOE proposed minimum air tightness, and uses no intentional mechanical (other than dryer exhaust) or natural ventilation by windows. The HUD Code home has an average air exchange rate of 0.42/h, with particularly high air exchange (above 1/h) during the coldest winter months. This results from both envelope leakage, which increases with wind speed and temperature difference between indoors and outdoors, and duct leakage, which increases with the amount of time that the furnace or air conditioner operates. A close look at the figure reveals that the individual days during each season with the highest AERs occurred on days with highest wind speeds. The proposed DOE standards would lower the average AER to 0.32/h and greatly reduce uncontrolled airflows during the cold winter months, with potential comfort benefits.

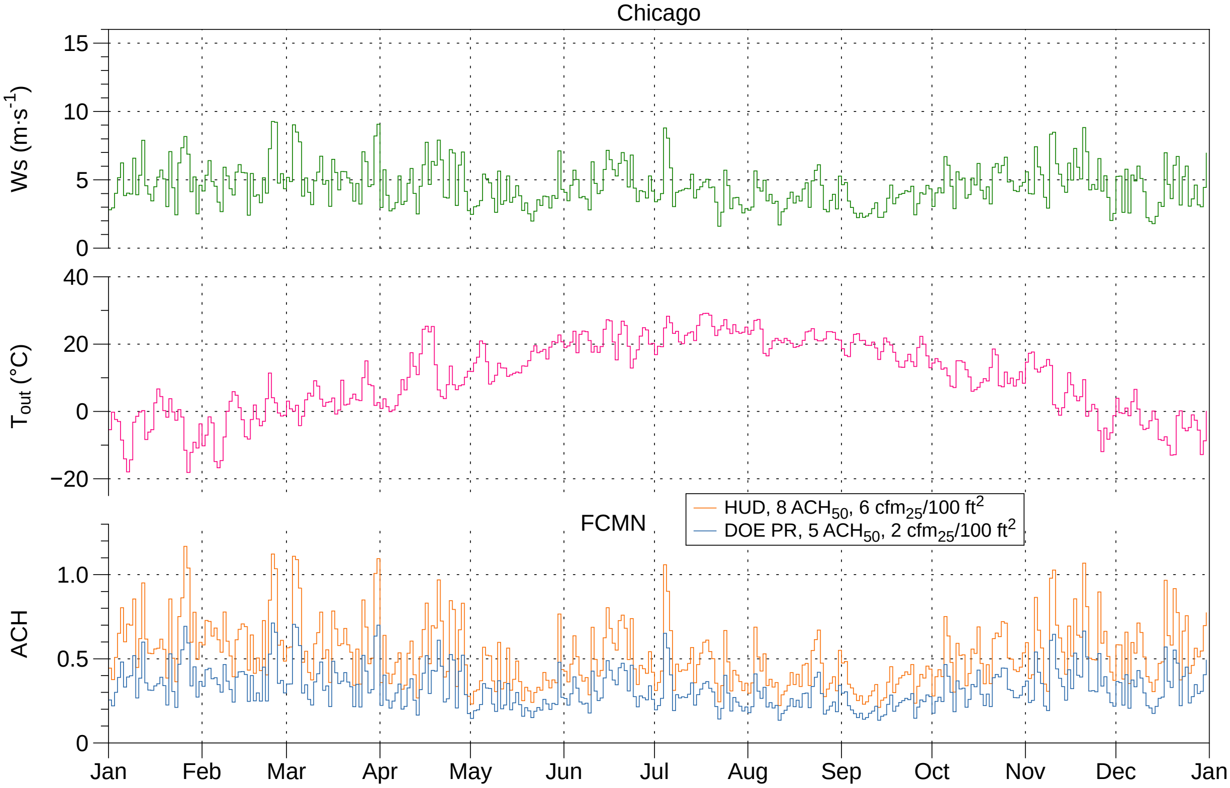

Figure 8 Modeled daily average air exchange rate for 1568 ft² manufactured home experiencing typical Chicago weather and not intentionally using any mechanical or natural ventilation (windows) with air leakage set at minimal level of HUD Code or proposed rule (DOE).

Figure 9 shows the daily AERs for the same Chicago home with a continuously operated CFIS supply ventilation system sized to provide 55 cfm during fan operation. In this case, the fan on the heating and cooling system operates 24/7 to provide ventilation, even when it is not being used for heating and cooling. Continuous operation is a HUD code requirement for this type of ventilation system. During operation of the central fan, outside air is added to the home both through the intentional CFIS inlet (55 cfm), as well as through unintentional duct leakage pathways (94 cfm). This approach leads to a high average AER of 0.72/h throughout the year. In comparison, ventilating a HUD code home with a continuous exhaust fan results in an AER of 0.53/h, because it does not have the extra airflow resulting from duct leaks. The proposed rule would reduce the AER for the home with continuous CFIS to 0.43/h and with a continuous exhaust ventilation fan to 0.37/h.

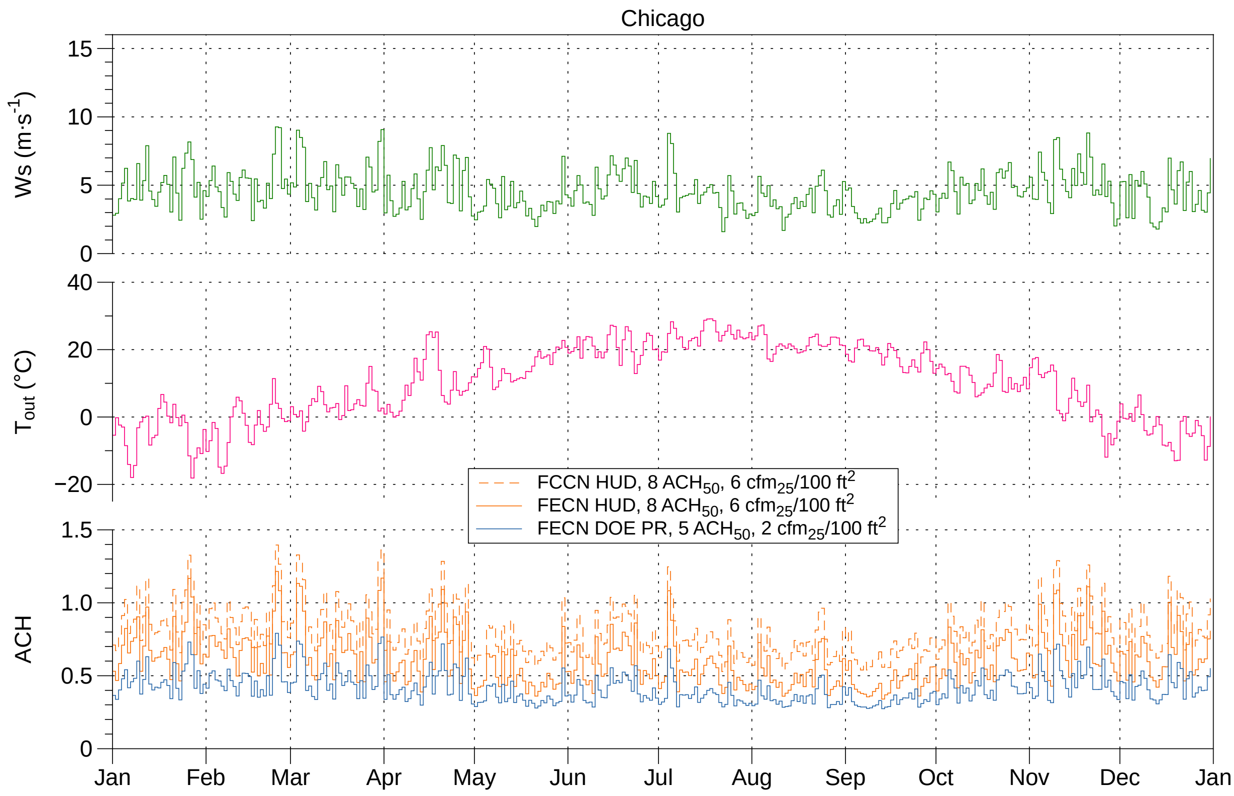

Figure 9 Modeled daily average air exchange rate for 1568 ft² manufactured home experiencing typical Chicago weather and using continuous mechanical ventilation with either a CFIS system or exhaust fan with air leakage at the minimum level of the HUD code (FCCN HUD, FECN HUD). The exhaust fan system is also shown with air tightness meeting the proposed rule (FECN DOE).

Figure 10 shows the calculated outdoor air exchange rates for the broad range of ventilation practices considered and for the two heating and cooling systems. Average daily values are shown as solid horizontal bars and 5th percentile daily values are shown with triangle plot symbols. The results are colored according to the envelope and duct leakage assumptions. Key results are summarized in Table 16.

As in the Chicago example, the DOE rule would reduce leak-driven average AERs in Fresno and Houston, enabling greater comfort and ventilation control, and potentially better protection from outdoor air pollution when needed. If windows are opened when no heating or cooling is required for at least 6 hours (scenarios with “W” in the 3rd position of the 4-letter code), average air exchange rates are much higher, but the lowest daily air exchange rates remain low. The patterns of air exchange are most impacted by the ventilation configuration and operation, with only secondary impacts associated with climate zone and type of heating and cooling equipment.

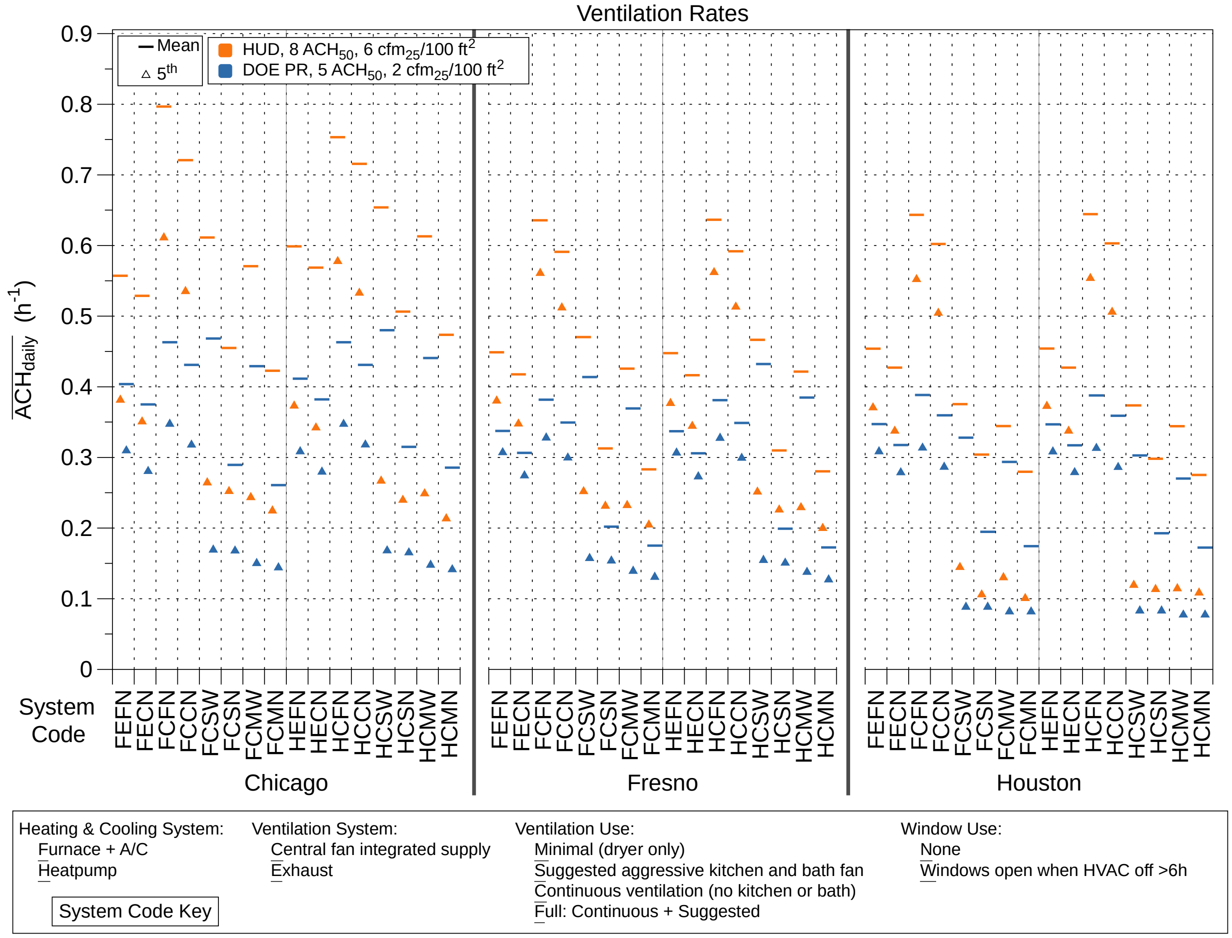

Figure 10 Estimated mean and 5th percentile of daily air exchange rates from simulations of a 1568 ft² home with varied airtightness and ventilation use.

Table 16 Air exchange rates estimated for a 1568 sf manufactured home having air leakage that is minimally compliant with current HUD Code or with the proposed rule and varied mechanical ventilation (MV).

Description	Chicago				Fresno				Houston			
	HUD	**DOE**	**Diff, 1/h**	**% Diff**	**HUD**	**DOE**	**Diff, 1/h**	**% Diff**	**HUD**	**DOE**	**Diff, 1/h**	**% Diff**
MV by central fan integral system only when heating/cooling	0.42	0.26	0.16	38%	0.28	0.18	0.11	38%	0.28	0.17	0.11	38%
MV by central fan integral only when heating/cooling + windows	0.57	0.43	0.14	25%	0.43	0.37	0.06	13%	0.34	0.29	0.05	15%
MV by central fan integral system operating all hours	0.72	0.43	0.29	40%	0.59	0.35	0.24	41%	0.60	0.36	0.24	40%
Mechanical ventilation by continuous exhaust fan	0.53	0.37	0.15	29%	0.42	0.31	0.11	27%	0.43	0.32	0.11	26%

Across all the scenarios (not just those shown in Table 16), the proposed rule would reduce MH ventilation rates by 7–42% and 0.03 to 0.33/h in absolute terms, with important variability depending on the ventilation configuration and smaller impacts by climate zone. Exhaust ventilation systems typically had reductions for 24–33% for the proposed rule, while CFIS systems had reductions in outside air ventilation of roughly 40%. HAC equipment type had little to no impact on air exchange results, so we only show results for systems with furnaces in Table 16. Changes in ventilation rates attributable to the proposed rule are least in cases with windows opened during mild weather periods, because the impact of window operation largely overwhelms the potential impacts of reduced envelope leakage.

3.2 NO_2 and $PM_{2.5}$ from Outdoors

Estimated annual average and the 95th percentile highest daily indoor concentrations of NO_2 and $PM_{2.5}$ coming from outdoors under the various ventilation scenarios are presented in Figure 11 and Figure 12. The analysis for these plots used regional median (typical) outdoor pollutant levels during each hour of the year, extracted from available data from the regulatory air monitoring stations within the boundaries for each area, shown in the map in Figure 3 (see additional details on outdoor pollution data in Section 2.2.2).

For NO_2, there are substantial differences across locations that derive from differences in the outdoor pollutant levels, with mean annual outdoor concentrations of 13, 8 and 6 ppb in Chicago, Fresno and Houston, respectively. Within each location, Figure 11 shows there are moderate variations in the average daily indoor NO_2 from outdoors for each airtightness level. The conditions that provide overall higher AERs (i.e., continuous CFIS, open windows and HUD code envelope configurations) generally have higher indoor levels of NO_2, but the variations are not proportional to air exchange. Across all ventilation conditions, the tighter envelopes and ducts required in the proposed rule will lead to reductions in the average indoor concentrations of outdoor NO_2: 15–27% for Chicago, 2–30% for Fresno, and -3 (slight increase)–30% for Houston. The largest benefit of the proposed rule occurs under "closed house" conditions of no intentional ventilation, as recommended when outdoor air pollution reaches hazardous levels, with reductions of 27–30% across the three locations. Use of a dedicated, continuous whole-house ventilation fan and also the range hood and bath fan will have an estimated reduction of 16–27% attributable to the proposed rule.

For $PM_{2.5}$, the outdoor levels across the three locations were much more similar than they were for NO_2, with annual mean outdoor $PM_{2.5}$ concentrations of 9, 11 and 8 μg/m^3 in Chicago, Fresno and Houston, respectively. Across ventilation conditions, the proposed rule will lead to reductions in the average indoor concentrations of outdoor $PM_{2.5}$ by 14–29% in Chicago, (-2)–29% in Fresno and (1)–28 percent in Houston. The smallest changes were for the window opening ventilation scenarios. Similar to NO_2, the largest benefit attributable to the proposed rule occurs under "closed house" conditions of no intentional ventilation, as recommended when outdoor air pollution reaches hazardous levels, with reductions of 25–29% across the three sites. Use of a dedicated, continuous whole-house ventilation fan and also the range hood and bath fan will have an estimated reduction of 14–29% based on changes in the proposed rule.

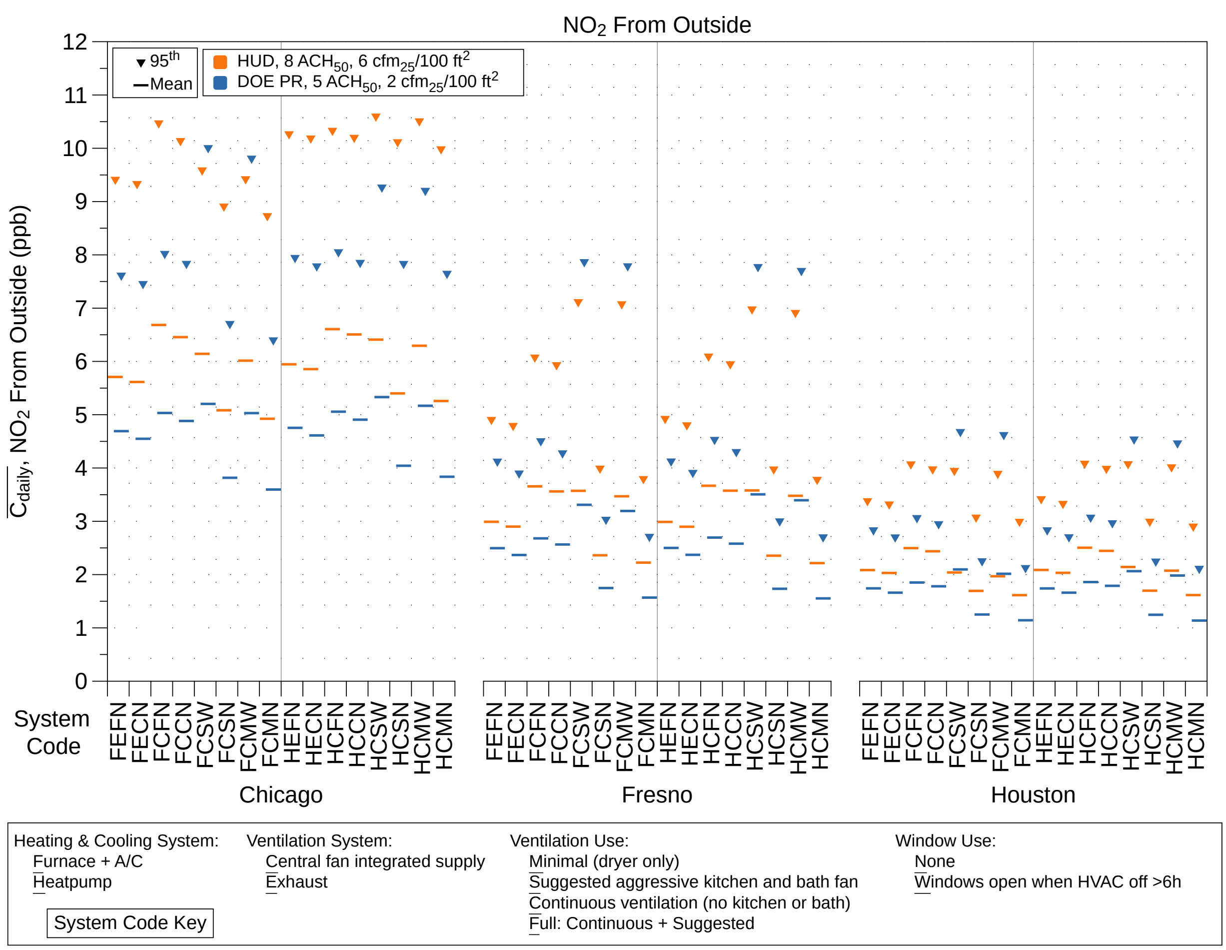

Figure 11 Simulation results for mean and 95th percentile daily concentrations of NO_2 from outdoor air.

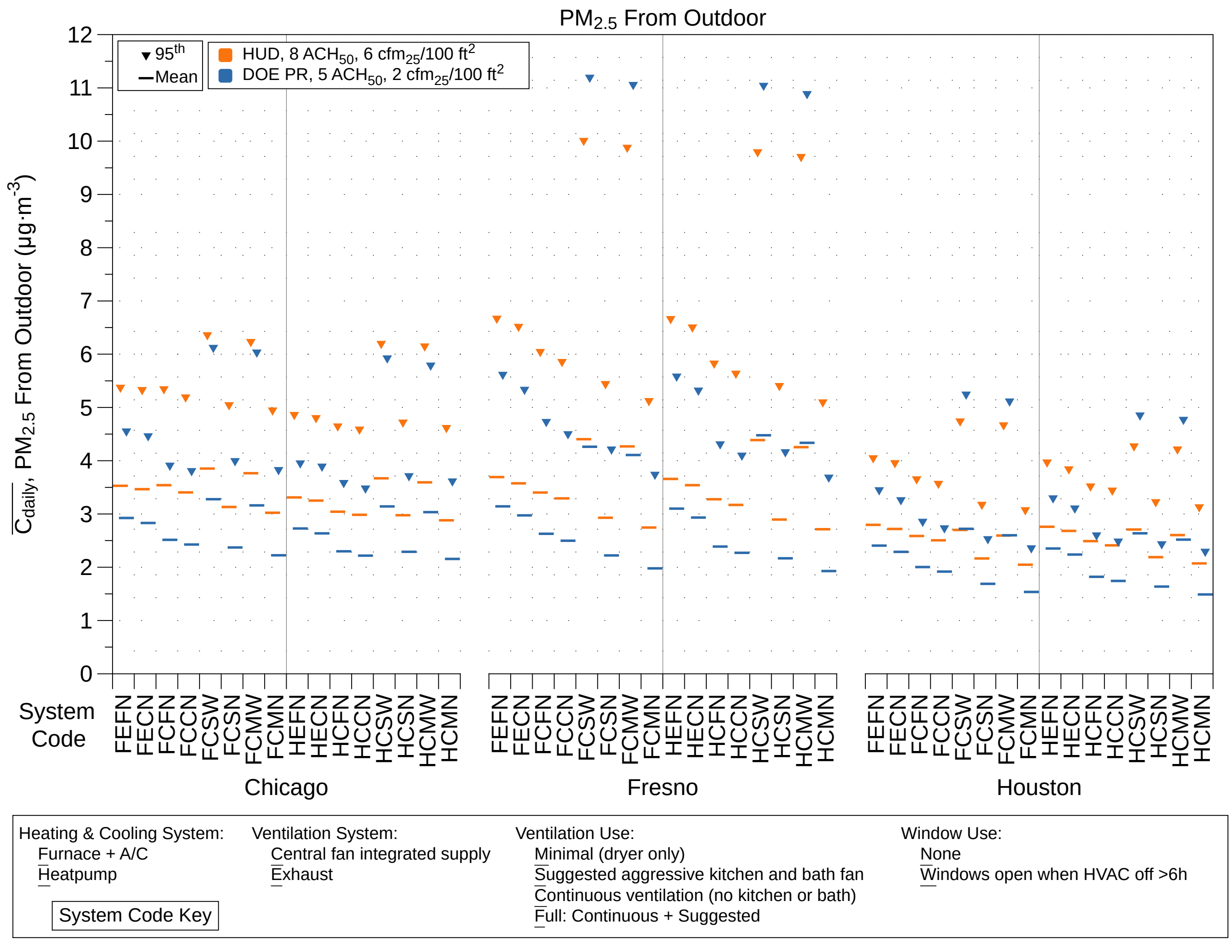

Figure 12 Simulation results for mean and 95th percentile daily concentrations of $PM_{2.5}$ from outdoor air.

3.3 Formaldehyde, Acrolein and Other Continuously Emitted Indoor Pollutants

Estimated formaldehyde concentrations under the various scenarios are presented in Figure 13. The impacts of ventilation and air-tightness on formaldehyde are informative of behavior for other continuously emitted pollutants. The following results are noteworthy.

- For a HUD Code home, average formaldehyde concentrations under the various scenarios are predicted to vary from 10 to 26 ppb. Use of continuous mechanical ventilation and window opening produce much lower levels than in homes with no intentional ventilation. Since the sources of these contaminants are indoors, increased ventilation provides benefits.
- Air sealing that is minimally compliant with the proposed rule is estimated to lead to increases in average formaldehyde concentrations ranging from 27 to 68% (to 16–40 ppb), across ventilation practices. Air sealing would lead to increases of 5.3–6.1 ppb (35–43%) in homes with continuous exhaust ventilation and 6.6–8.4 ppb (63–68%) in homes with continuous CFIS ventilation and no use of kitchen or bath ventilation. In homes using either type of continuous ventilation, average formaldehyde concentrations in the tighter homes would remain below about 23 ppb, similar to what was observed in two recent studies of

modern site-built homes with mechanical ventilation (Singer et al., 2020)(Rosenberg, S.I. et al., 2020).

- Air sealing is expected to lead to higher 95th percentile (high) formaldehyde days, with increases of 20–73% across ventilation scenarios. With continuous ventilation, the high days are predicted to remain at 25 ppb or below. Without continuous ventilation, formaldehyde on the high days is estimated to reach 45 ppb in Chicago, 53 ppb in Fresno and 55 ppb in Houston.
- Across the three cities, the smallest relative changes resulting from the proposed minimum air-tightness requirements will occur in homes using continuous exhaust ventilation. In these homes, concentrations of continuously emitted pollutants like formaldehyde would increase by 31–68% for average days and by 20-73% for 95th percentile days.
- Variations in duct leakage in current HUD Code homes cause very small differences; but large duct leakage impacts occur for homes that operate CFIS ventilation continuously.
- Within each city, similar patterns are present for homes using a conventional furnace and air conditioner or a heat pump, and the patterns across system configurations are similar between cities.

The calculated acrolein concentrations resulting from continuous emissions under varied scenarios are presented in

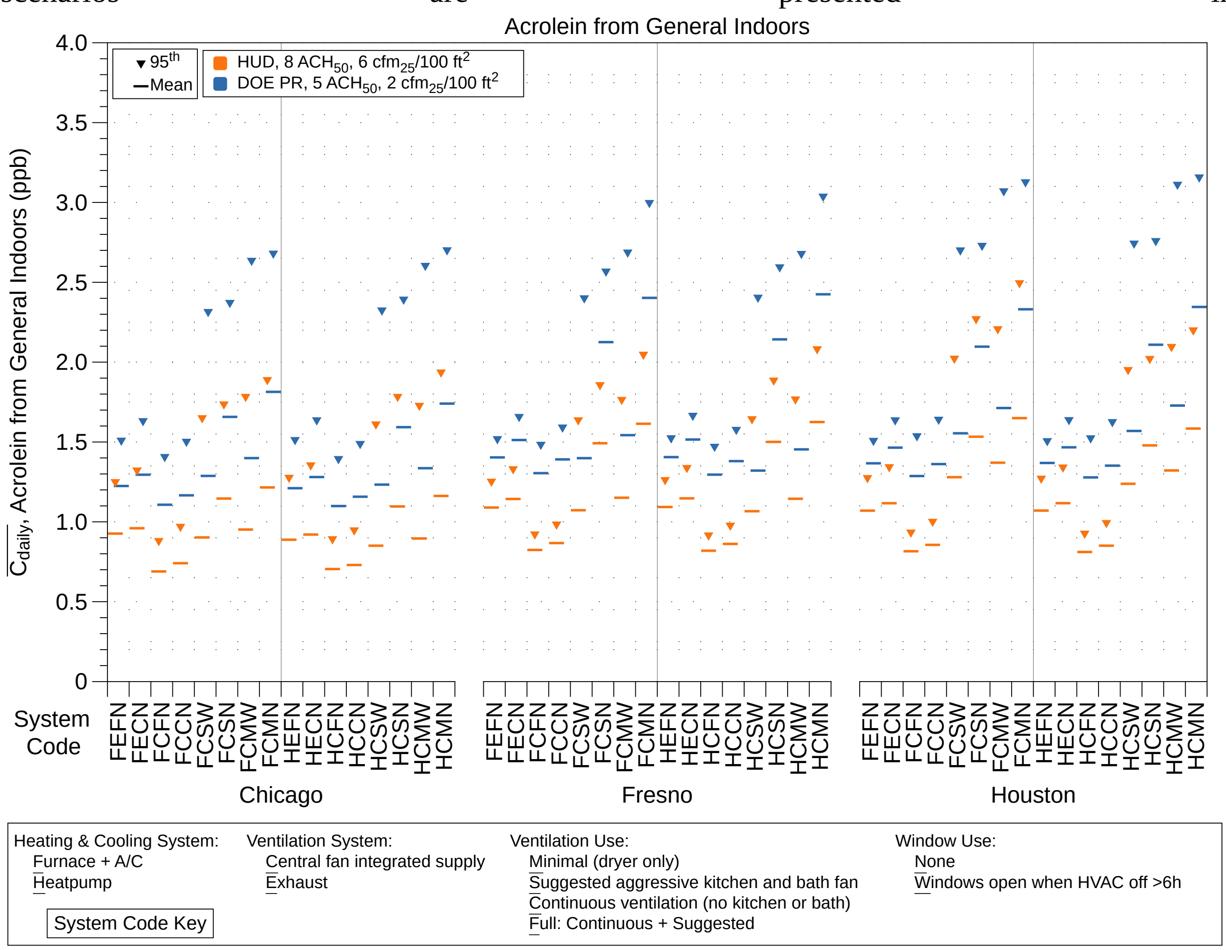

Figure 14. The pattern of results for continuous acrolein are almost identical to those for formaldehyde, demonstrating that they are generalizable to other continuously emitted pollutants. Minor differences result from the small sorption loss of 0.04/h assumed for acrolein.

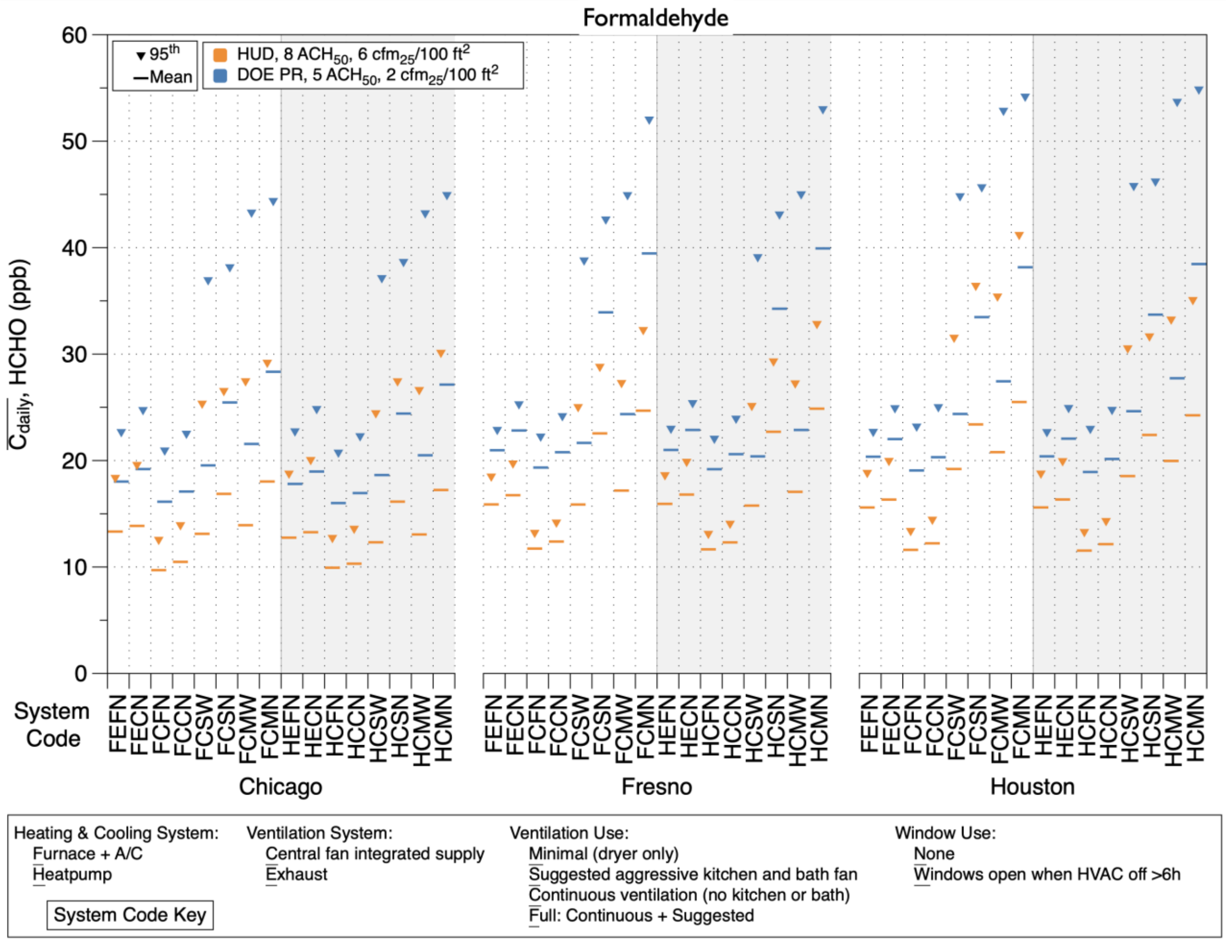

Figure 13 Simulation results for mean and 95th percentile daily concentrations of formaldehyde from constant emissions.

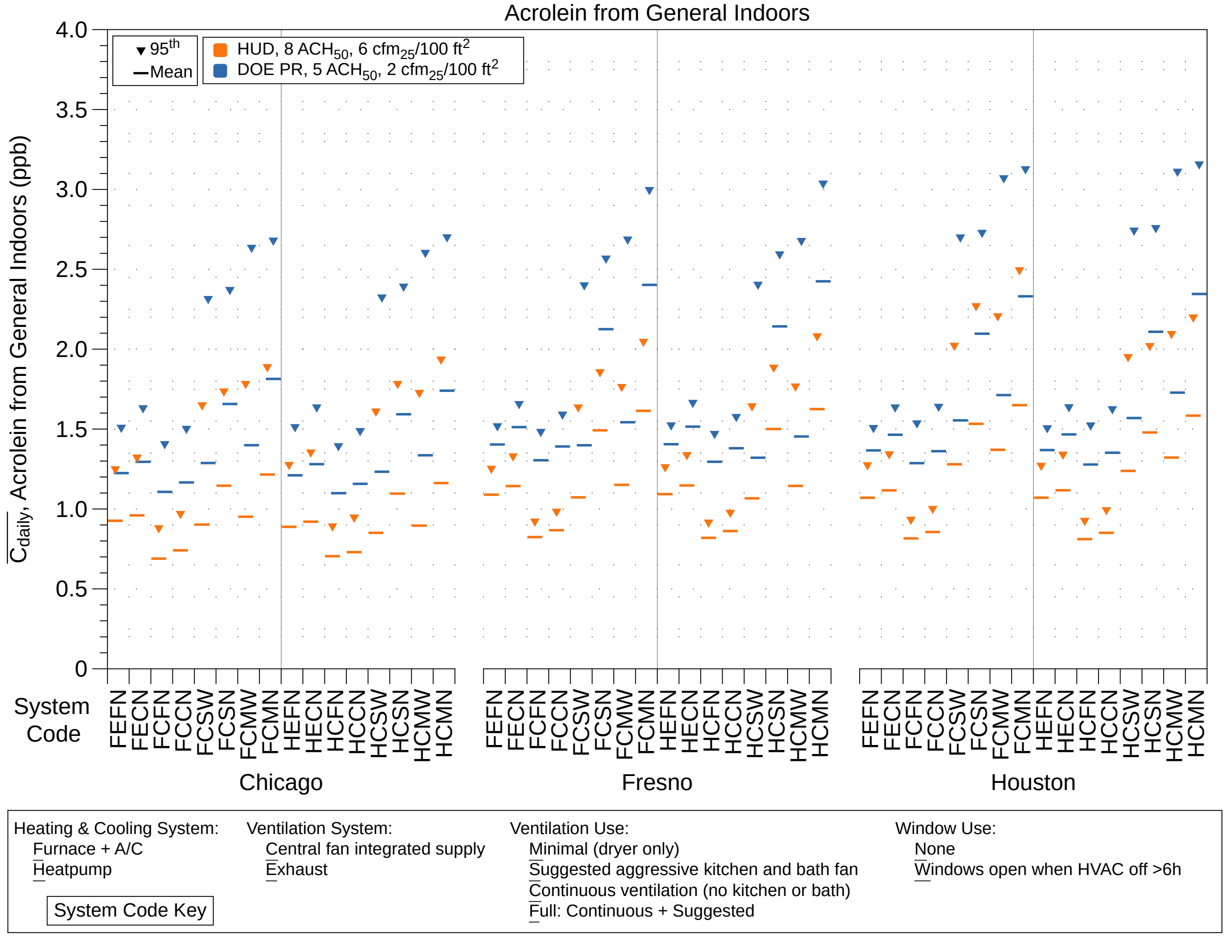

Figure 14 Simulation results for mean and 95th percentile daily concentrations of acrolein from constant emissions.

3.4 PM2.5 from Non-Cooking Activities

Estimated concentrations of PM2.5 emitted by miscellaneous occupant activities during waking hours under varied ventilation scenarios are presented in Figure 15. The patterns of activity-related PM2.5 across ventilation scenarios differ from those of formaldehyde and acrolein, primarily owing to the effect of filtration in the central heating and cooling system.

- Even with the 10% efficient filter used in the modeling, the high airflows assumed for the single-speed heating and cooling equipment provides substantial particle removal.
- This filtration effect is particularly apparent in households that can afford and choose to operate CFIS ventilation systems continuously. Average concentrations in homes with continuous CFIS are estimated to be 3.1–3.6 µg/m^3 in HUD Code homes, increasing to 3.7–4.4 µg/m^3 (increases of 17–28%) for homes complying with the DOE proposed rule. The 95th percentiles for HUD Code homes are estimated to be 3.4–4.1 µg/m^3, increasing to 4.0–4.6 µg/m^3 (increases of 14–28%) with improved air tightness.
- In homes not utilizing routine ventilation of any kind (FCMN and HCMN), average PM2.5 is estimated to be 4.7–5.3 µg/m^3 for homes meeting the HUD code and 5.3–6.3 µg/m^3 (increases of 15–19%) for homes meeting the DOE rule. The 95th percentiles for HUD Code homes are estimated to have 5.9–6.3 µg/m^3, increasing to 6.6–7.0 µg/m^3 (increases of 10–13%) with improved air tightness.

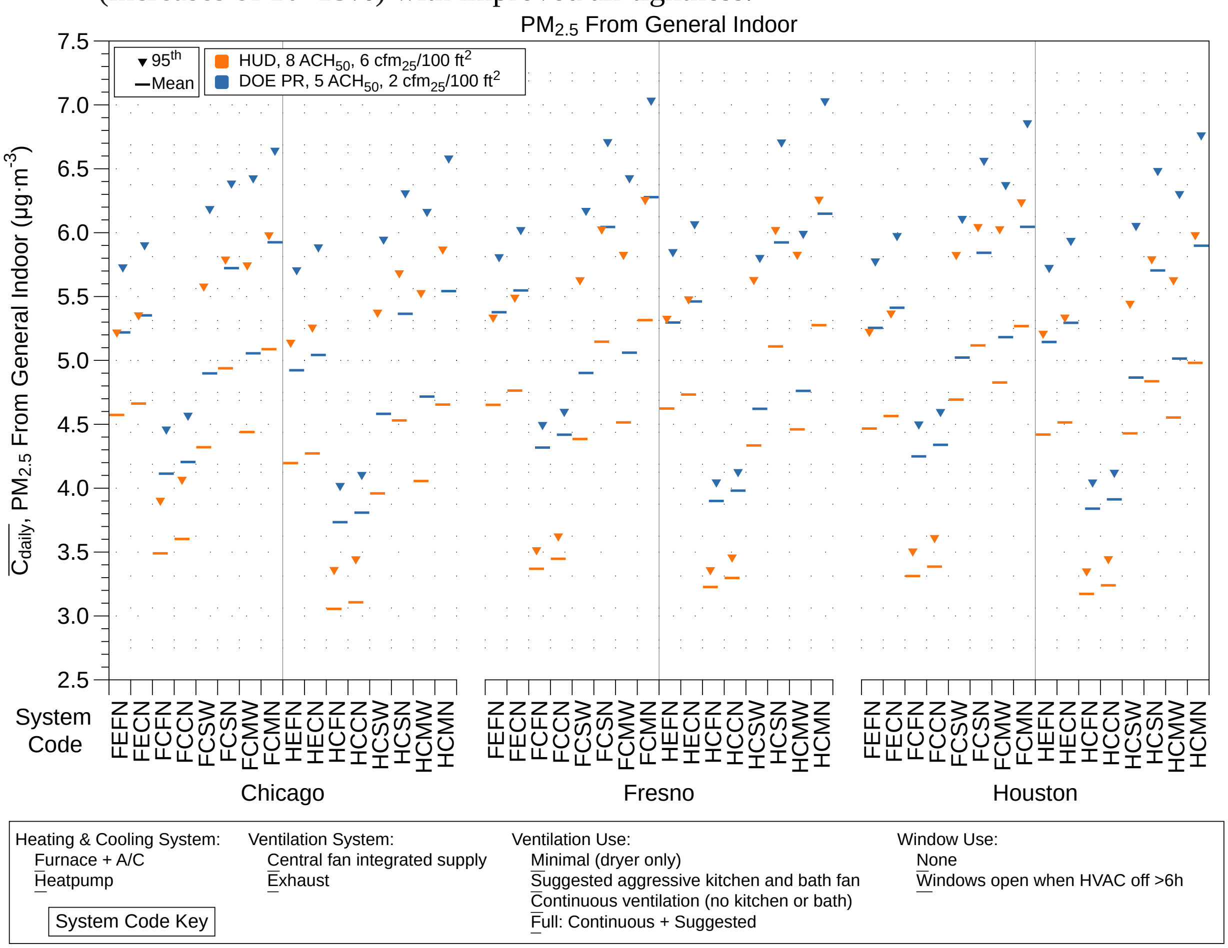

Figure 15 Simulation results for mean and 95th percentile daily concentrations of PM2.5 from occupant activities.

3.5 Acrolein, NO_2, and $PM_{2.5}$ from Frequent Cooking

This section presents results from three pollutants emitted during cooking events assuming a natural gas or propane stove. It is critical to note in discussing cooking contaminant concentrations that the 95th percentile values we present are the daily mean values for the 95th percentile day of the year for homes with the amount of cooking assumed for the analysis, not the 95th percentile hourly or minutely concentration recorded in the dwelling, and not the 95th percentile reflecting variable emissions across the population of manufactured homes. Additionally, readers are reminded that the modeling was for volume-average concentrations in the house, assuming all emitted mass is instantaneously well-mixed. In real homes, concentrations will be higher in the kitchen then connected areas in the time during and just after cooking, and short-term concentrations averaged throughout the house will be higher than the daily average. And there are many days in many homes during which cooking related emissions are higher than even the high intensity cooking assumed for this analysis.

Across all three contaminant species, the modeled use (or non-use) of the kitchen range hood was a critical factor in determining indoor concentrations and impacts of the proposed rule. When used during cooking, the kitchen range hood was assumed to remove 60% of the cooking-related emissions prior to mixing with the air in the home. In real homes with varied cooking behaviors, varied range hood products and usage patterns (e.g., the choice of setting, cooking on front vs. back burner, etc.), the performance of range hoods varies widely. Envelope air leakage consistent with the proposed rule increased concentrations of all three cooking-related contaminants, but these increases were smallest in homes using the kitchen range hood, with window operation during mild weather, and with continuous mechanical ventilation.

Estimated acrolein concentrations resulting from frequent cooking are presented in Figure 16.

- For a HUD Code home, average acrolein in simulations with frequent cooking vary from 0.33 to 2.52 ppb across ventilation conditions. Improved air tightness of the proposed rule would increase concentrations by 29-76%, resulting in concentrations of 0.58–3.60 ppb.[6]
- On the 95th percentile days in HUD Code homes, acrolein from frequent cooking is estimated to be 0.70–5.75 ppb. In homes constructed to DOE's proposed standards, acrolein from frequent cooking is estimated to be 1.16–7.49 ppb (+28–75%).
- Use of the kitchen range hood makes the biggest difference for controlling exposures. Average acrolein from frequent cooking is estimated at 0.33–0.87 ppb in a HUD Code home using a range hood during cooking, increasing to 0.58–1.21 in a home meeting the proposed rule with similar ventilation. Without range hood use, average acrolein from cooking in the HUD Code home is estimated to be 0.94–2.52 ppb. In homes meeting the airtightness requirements of DOE's proposed rule, frequent cooking without range hood use is estimated to yield acrolein at 1.62–3.60 ppb (31–73% increase, across homes in the subgroup).

[6] Acrolein concentrations are presented with two decimal places to maintain precision for numbers that extend from the low single digits, down to below 1.0. Other pollutant concentrations are presented with one decimal place because they are mostly above 3.0. This simplified approach is used in place of the convention of setting a fixed number of significant figures, which would result in varied decimal places for the same pollutant.

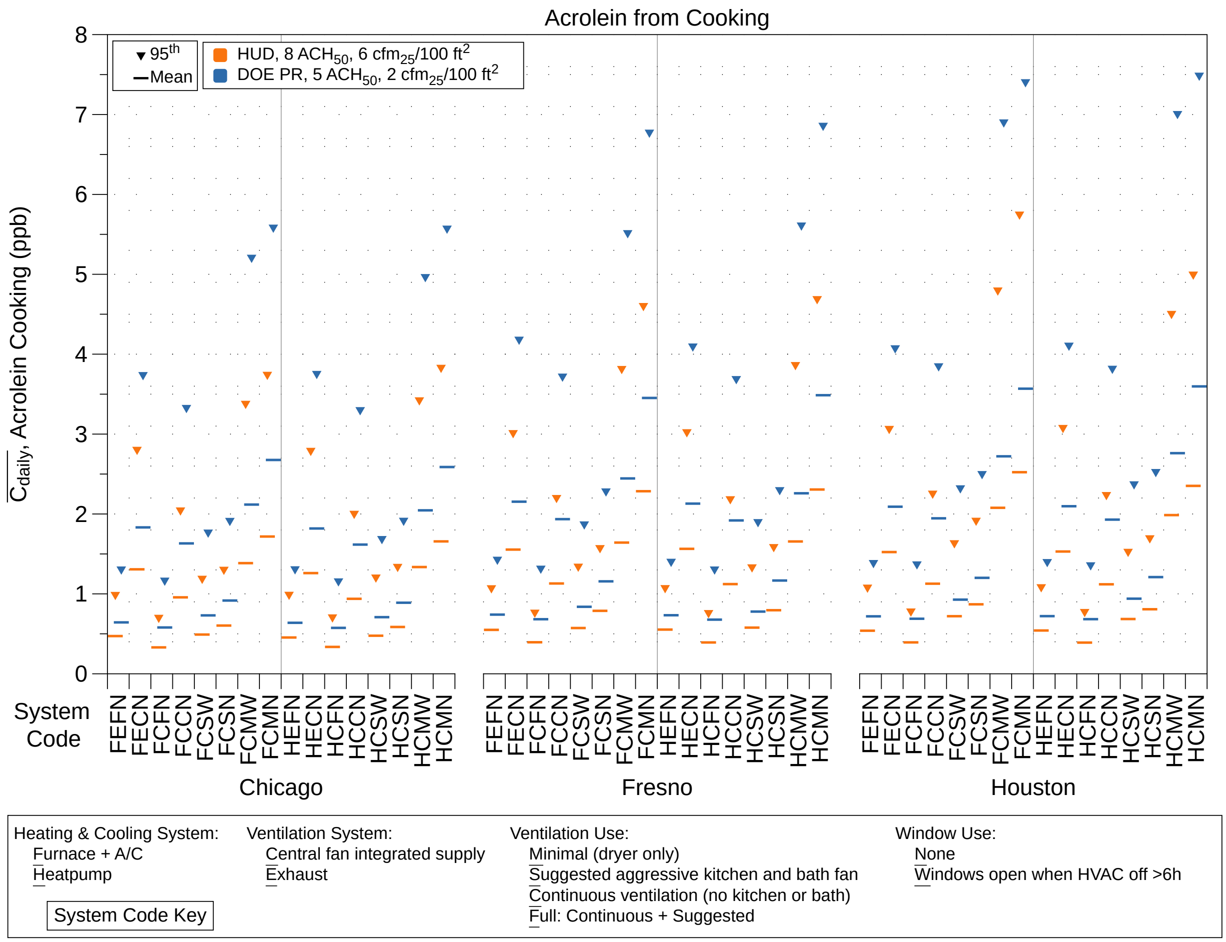

Figure 16 Simulation results for mean and 95th percentile daily concentrations of acrolein from frequent cooking in a home with natural gas or propane cooking appliances.

Estimated NO_2 concentrations resulting from frequent cooking are presented in

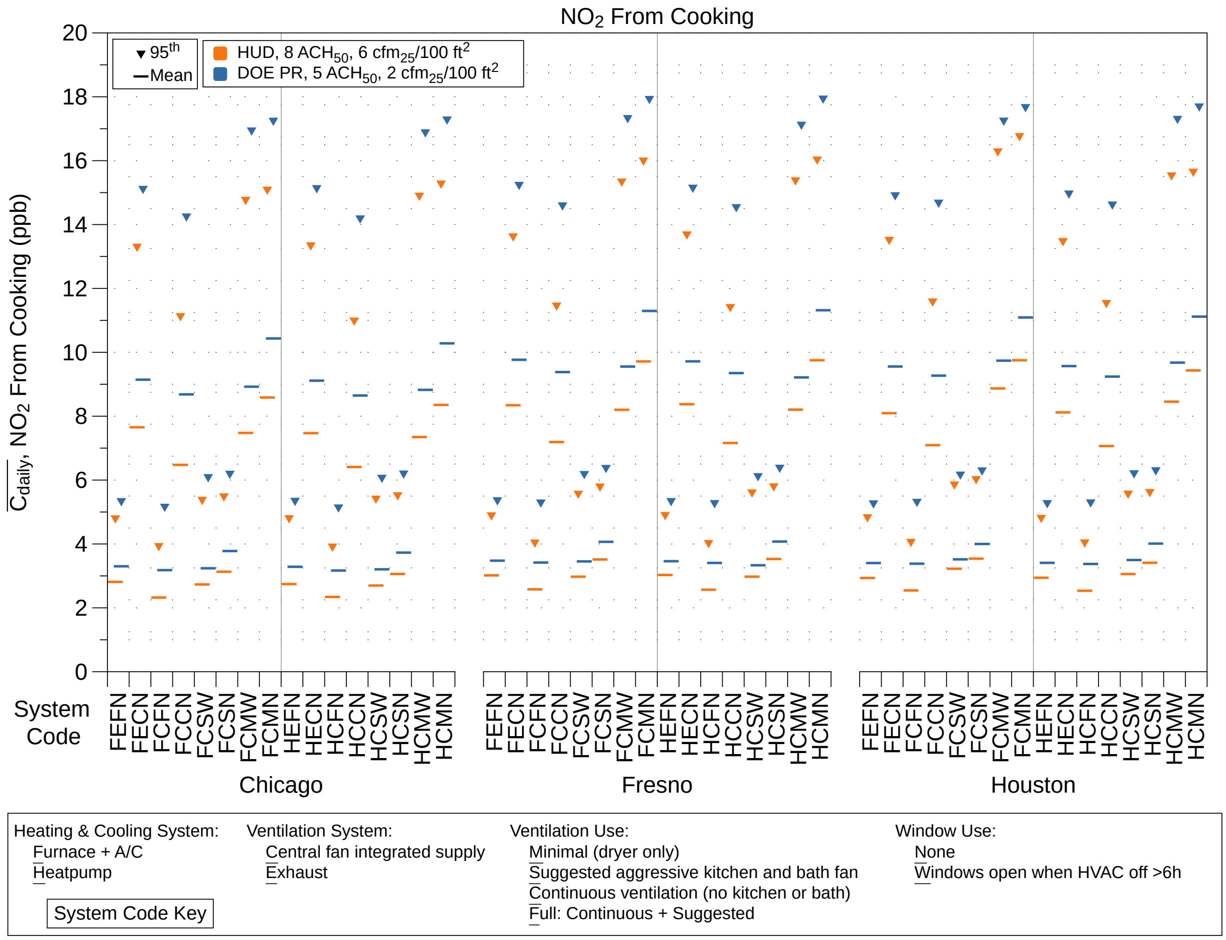

Figure 17.

- Similar to acrolein, simulated use of the range hood results in much lower concentrations of NO_2 from cooking. Average and 95th percentile NO_2 for Full and Suggested ventilation scenarios (both of which include range hood use) are estimated to be 2.3–3.5 ppb and 3.9–6.0 ppb from intensive cooking in the HUD code home. Using the range hood with air tightness at the levels of the proposed rule is predicted to result in average and 95th percentile NO_2 from cooking of 3.2–4.1 ppb and 5.2–6.4 ppb, corresponding to increases of 9–37% and 5–31%.
- When the range hood is not used, intensive cooking is estimated to produce much higher average and 95th percentile NO_2 concentrations: 6.4–9.8 ppb and 11.0–16.8 ppb in a HUD Code home, and 8.6–11.3 ppb and 14.2–18.0 ppb in a home with air tightness consistent with the proposed rule.
- When not using a range hood, opening windows (-CMW) reduces average NO_2 compared to no windows (-CMN), but the control has a smaller relative impact on the 95th percentiles.

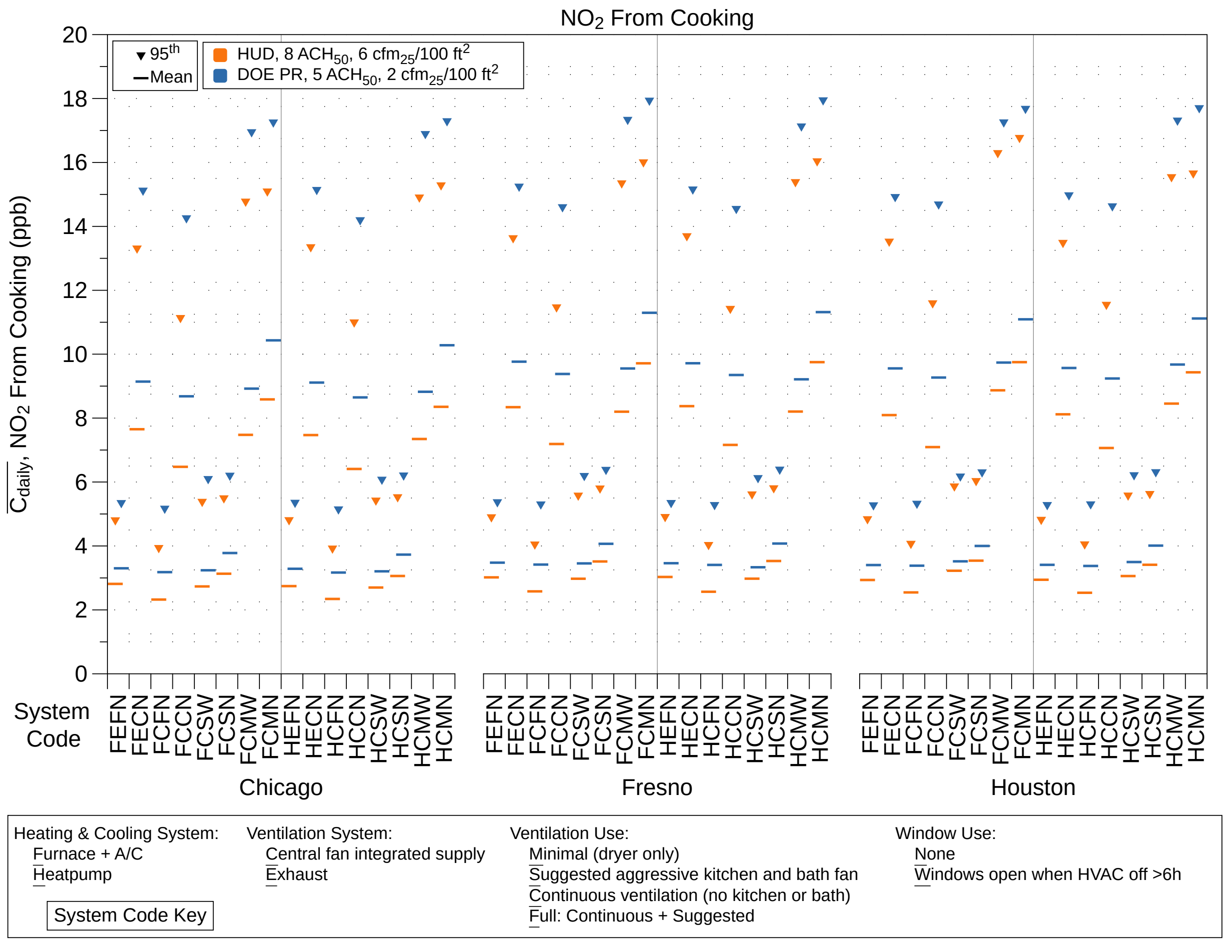

Figure 17 Simulation results for mean and 95th percentile daily concentrations of NO_2 from frequent cooking in a home with natural gas or propane cooking appliances.

Estimated $PM_{2.5}$ concentrations resulting from frequent cooking are presented in Figure 18.

- Average and 95th percentile $PM_{2.5}$ for ventilation scenarios that include range hood use are estimated to be 1.4–3.3 µg/m^3 and 2.6–6.3 µg/m^3 for frequent cooking in the HUD code home. Increasing airtightness to the levels of the proposed rule is predicted to increase average $PM_{2.5}$ by 9–51% across scenarios (to 2.0–4.1 µg/m^3), and to increase 95th percentile daily mean $PM_{2.5}$ by 8–49% (to 3.6–7.4 µg/m^3) when the range hood is used.
- When the range hood is not used, intensive cooking is estimated to produce much higher average and 95th percentile $PM_{2.5}$ concentrations: 3.9–9.2 µg/m^3 and 7.0–17.4 µg/m^3 in a HUD Code home, and 5.2–11.2 µg/m^3 and 9.7–20.5 µg/m^3 in a home with air tightness consistent with the proposed rule.
- Opening windows when not using the range hood (-CMW) reduces average cooking-related $PM_{2.5}$, but this control has a smaller relative impact on the 95th percentiles.
- As seen for $PM_{2.5}$ from miscellaneous occupant activities, continuous operation of a CFIS ventilation system can provide substantial filtration benefit. The Full ventilation scenarios that included both range hood use and continuous CFIS operation (FCFN and HCFN)

resulted in the lowest PM2.5, with average concentrations of 1.4–1.8 μg/m^3 for a HUD Code home and 2.0–2.5 μg/m^3 for a home complying with air tightness requirements of the proposed rule.

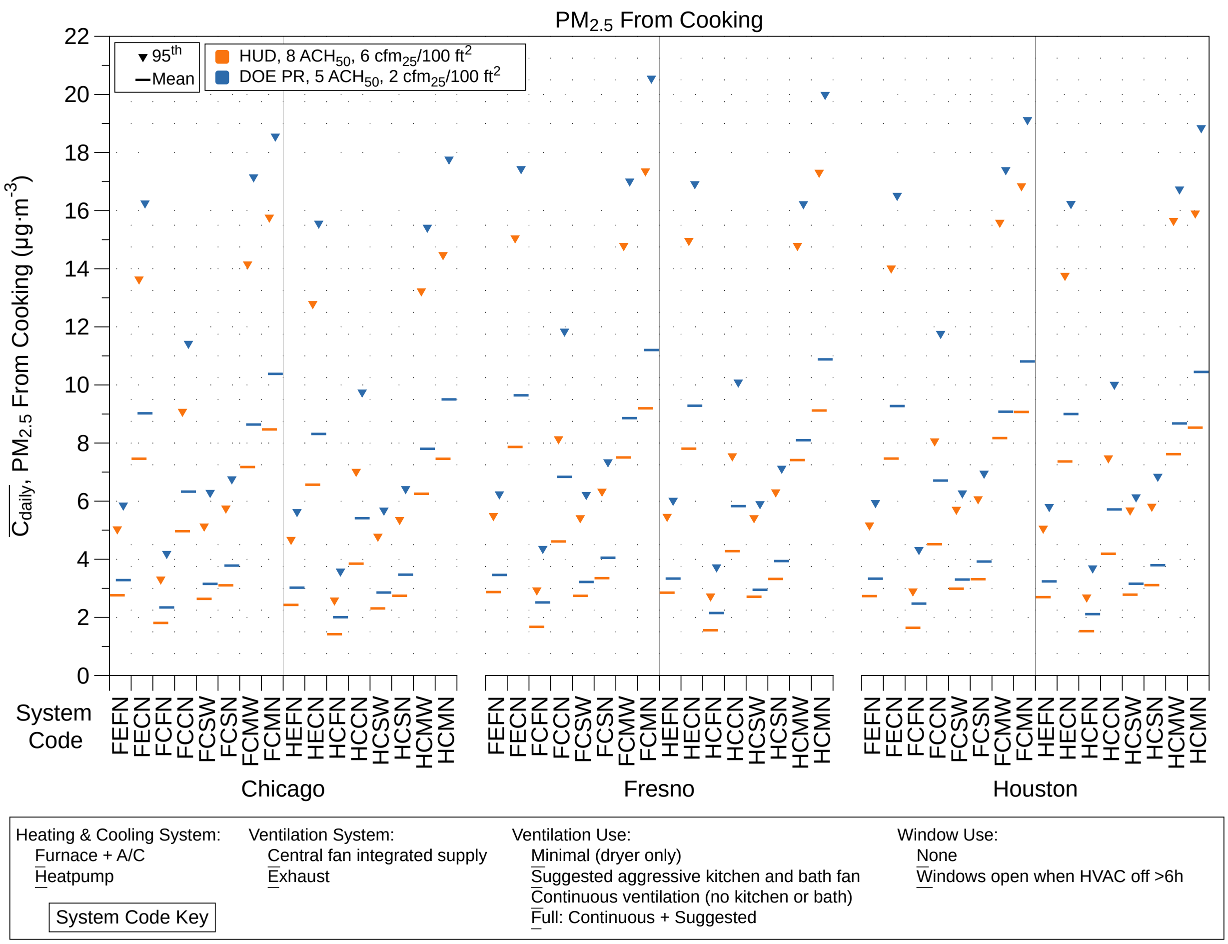

Figure 18 Simulation results for mean and 95th percentile daily concentrations of PM2.5 from frequent cooking in a home with natural gas or propane cooking appliances.

3.6 Total Acrolein from Typical Cooking and Continuous Sources

Estimates of the overall impacts of improved airtightness on indoor concentrations of acrolein are provided for the three sites and various ventilation scenarios in Figure 19. Across all scenarios, the average total acrolein concentrations for the home with HUD Code airtightness is estimated to be 0.85–2.91 ppb. Values for individual scenarios would increase by 23–65% to 1.39–4.17 ppb. The 95th percentile highest days are estimated to be 1.17–5.10 ppb under HUD Code and increase by 22–65 % to 1.88–6.65 ppb under DOE's proposed standards. Across the three locations, HUD Code homes without use of ventilation are estimated to have average acrolein of 1.99–2.92 ppb.

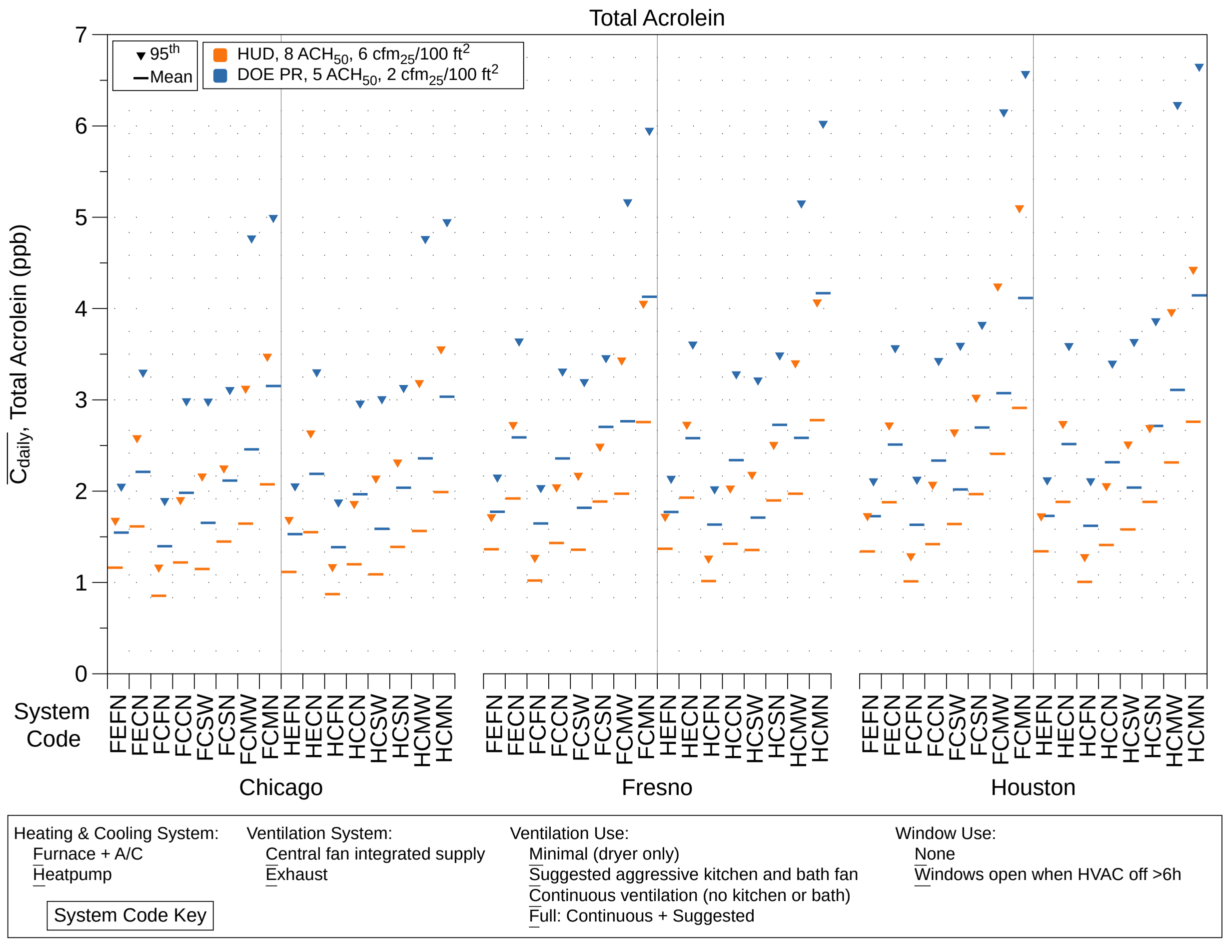

Figure 19 Simulation results for mean and 95th percentile daily concentrations of indoor acrolein from all sources.

3.7 Total Nitrogen Dioxide from Typical Cooking and Outdoors

Estimates of the overall impacts of improved air tightness on indoor concentrations of NO_2 are provided for the three sites and various ventilation scenarios in Figure 20.

Across all scenarios, the average total NO_2 concentrations for the home with HUD Code airtightness is estimated to be 3.4-10.0 ppb. Increasing airtightness and other efficiency measures to meet DOE's proposed standards but keeping other factors constant would produce changes to total average NO_2 varying from a 16 percent reduction (by reducing indoor concentrations of NO_2 from outdoors) to an 8 percent increase, to a range of 3.3-9.6 ppb. The 95th percentile highest days are estimated to be 5.1-13.8 ppb under HUD Code and change by -17 percent to +12 percent with the improved air tightness of DOE's proposed standards to a range of 4.9-13.8 ppb. Substantial reductions were estimated for Chicago, which had the highest outdoor NO_2.

Across the three sites, HUD Code homes without ventilation use are estimated to have average NO_2 of 6.3-9.4 ppb. Homes conforming with DOE's proposed standards and using continuous exhaust whole-house ventilation would have average NO_2 of 6.4-9.2 ppb. Homes using a

60 percent effective range hood during cooking but not using continuous whole-house mechanical ventilation would have average NO_2 of 3.3–5.9 ppb. Use of a continuous whole-house ventilation fan (not CFIS) and range hood would result in NO_2 concentrations of 3.4-6.4 ppb in the same locations, with the same emissions. As with acrolein, increased use of continuous whole-house or kitchen exhaust ventilation, or both, could effectively offset any increases from air sealing.

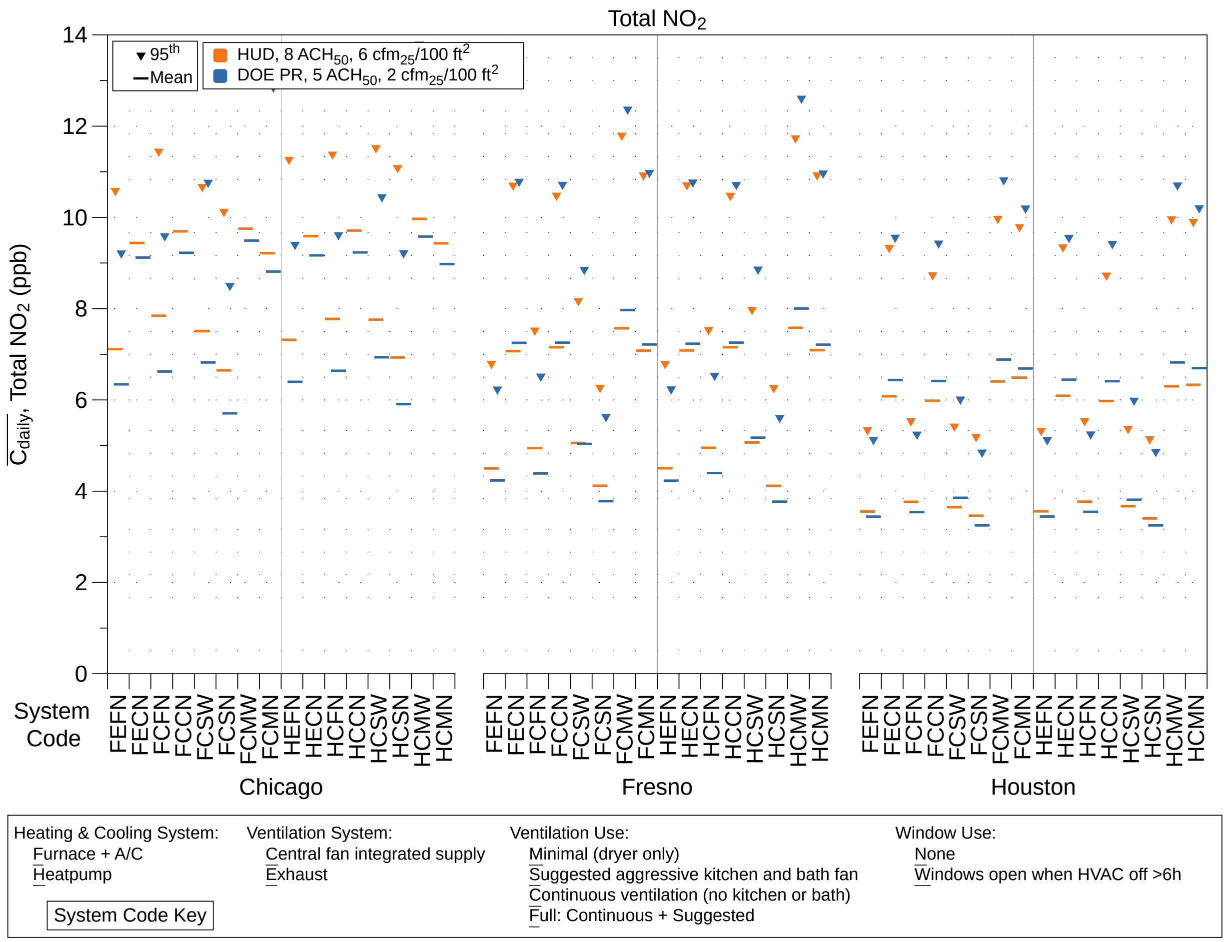

Figure 20 Simulation results for mean and 95th percentile daily concentrations of indoor NO_2 from all sources.

3.8 Total $PM_{2.5}$ from Miscellaneous Occupant Activities, Typical Cooking and Outdoors

Estimates of the overall impacts of improved air tightness on indoor concentrations of $PM_{2.5}$ are provided for the three sites and various ventilation scenarios in Figure 21. Across all scenarios, the average total $PM_{2.5}$ concentrations for the home with HUD Code airtightness is estimated to be 6.4-12.7 $\mu g/m^3$. Across the three sites, HUD Code homes without ventilation use are estimated to have average $PM_{2.5}$ of 11.3–12.7 $\mu g/m^3$.

Homes conforming with DOE's proposed standards and using continuous exhaust whole-house ventilation would have average $PM_{2.5}$ of 11.8-13.3 $\mu g/m^3$. Homes using a 60 percent effective range hood during all cooking but not continuous whole-house mechanical ventilation would have average $PM_{2.5}$ of 9.2-10.3 $\mu g/m^3$. Use of a continuous whole-house ventilation fan (not CFIS) and range hood would result in $PM_{2.5}$ concentrations of 9.1–10.3 $\mu g/m^3$ in the same locations and with the same emissions. As with acrolein and NO_2, increased use of continuous whole-house or kitchen exhaust ventilation, or both, could effectively offset increases from air sealing. Operation of an air cleaner or installation of a more efficient central heating and cooling system filter would also reduce $PM_{2.5}$.

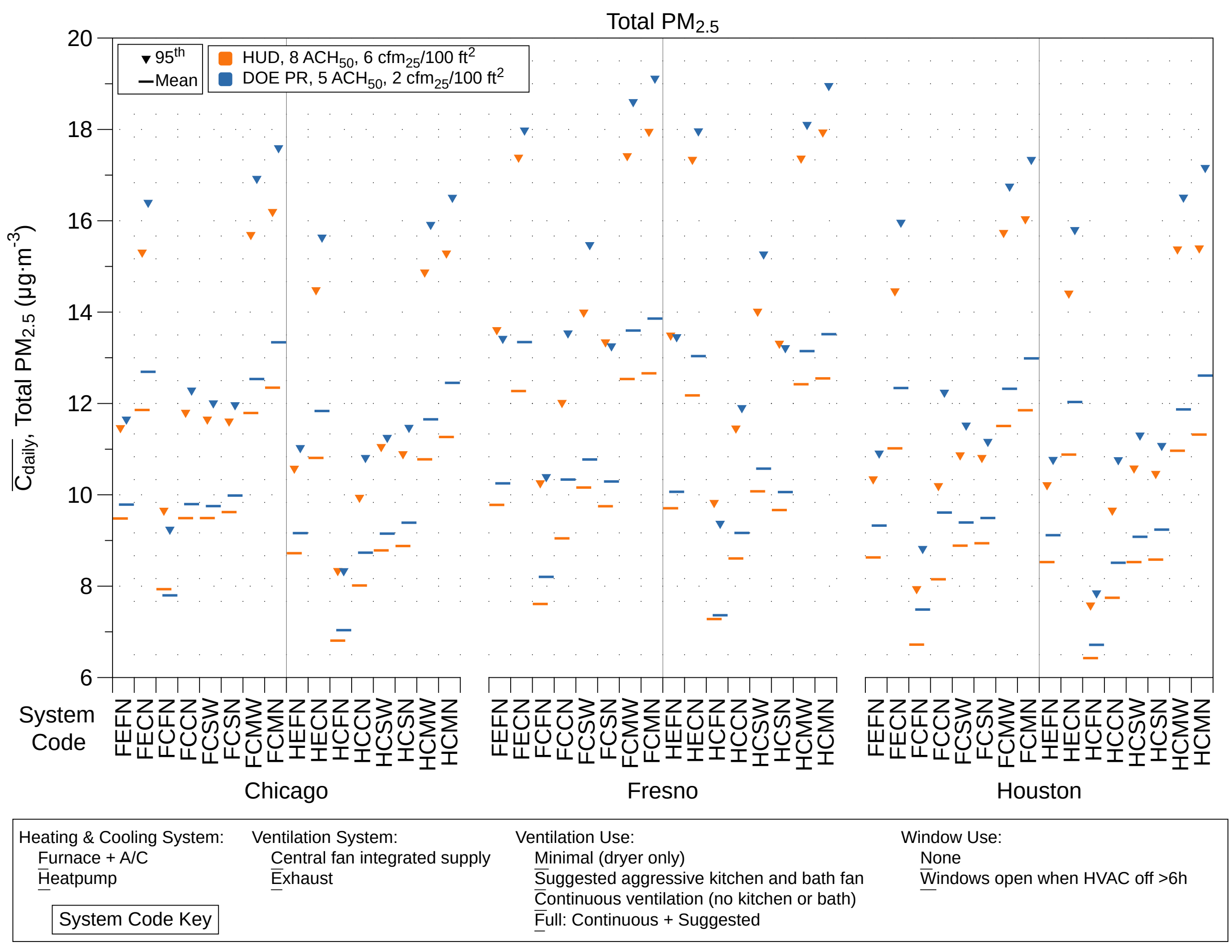

Figure 21 Simulation results for mean and 95th percentile daily concentrations of indoor $PM_{2.5}$ from all sources.

3.9 Summary of Model-Predicted IAQ Impacts

The analyses summarized above found that DOE's proposed standards are expected to lead to substantial improvements in the protection that manufactured homes provide to occupants against outdoor air pollution. Under closed house conditions, with ventilation systems temporarily turned off as recommended during outdoor air pollutant events, homes built to DOE's proposed air tightness standards would have indoor concentrations of outdoor NO_2 and $PM_{2.5}$ that are about 25-30 percent lower than would occur in a HUD Code home.

The analysis also found that the estimated increase in concentrations of pollutants from indoor sources is of similar magnitude to the decreases for outdoor contaminants.

- For continuously emitted volatile organic compounds, the increase is estimated to be 21–68 percent across all ventilation practices, but only 31-43 percent in homes using continuous exhaust ventilation.
- $PM_{2.5}$ from occupant activities would increase by 7–28 percent across all scenarios and by 15–19 percent in homes using continuous exhaust ventilation.
- Acrolein and other gases from cooking would increase by 29–76 percent across all the ventilation scenarios and by 36–44 percent in homes using continuous exhaust ventilation.
- $PM_{2.5}$ from cooking would increase by 9–51 percent across all ventilation scenarios and by 19–27 percent in homes using continuous exhaust ventilation.
- NO_2 from gas cooking burners would increase by 9–37 percent across all ventilation scenarios and by 16–22 percent in homes using continuous exhaust ventilation.
- Compared to a HUD Code home that does not use mechanical ventilation, a home meeting DOE's proposed standards that uses continuous exhaust ventilation would have formaldehyde concentrations that are 14 percent lower to 10 percent higher across the three locations.
- Compared to a HUD Code home that does not use mechanical ventilation, a home meeting DOE's proposed standards that uses a range hood during all cooking would have cooking-related acrolein concentrations that are 46–52 percent lower. The reduction would be 55–59 percent lower for NO_2 from gas cooking burners and 53–57 percent for $PM_{2.5}$ from cooking.

This analysis of potential IAQ impacts of the proposed energy conservation standards for manufactured housing addresses two example cases that aligned with Alternative D (no action) and Alternative C1 (untiered standard with insulation per IECC 2021 specifications) of the proposed rule. Because the untiered standard would have aligned with Tier 2 of the tiered standards, this analysis also illustrates potential IAQ impacts for Tier 2 of Alternative A1 (price-based tiered standard with insulation per IECC 2021 specifications) and Tier 2 of Alternative B1 (size-based tiered standards with insulation per IECC specifications). Furthermore, the estimated impacts presented in this section are thought to generally apply to the other action alternatives, because each action alternative includes improved air sealing of the envelopes and ducts.

Under the no-action alternative (Alternative D), occupants of manufactured homes would continue to be exposed to air pollutants at widely varying concentrations that depend on where they live (contributions of outdoor air pollutants), the materials used to construct the homes, what they do in the homes (including cooking and recreational combustion such as candles, incense and smoking), and very importantly, whether and how they operate ventilation and utilize filtration to manage their indoor air quality.

4 Limitations and Caveats

This study is limited both in (1) the degree to which the models accurately simulate the physical processes that would occur for the set of discrete conditions considered, and (2) the extent to which the consideration of only a few variables and the use of only one value each for many parameters provides insights to effects across the population.

The following specific issues are noted in relation to the accuracy with which the model simulates key physical processes:

- The HAC system runtimes calculated by Energy Plus are based on lowest first cost equipment that operates with only a single stage of thermal conditioning (single rate of heating or cooling) and a single speed blower. Multistage equipment and multispeed blowers would result in different HAC equipment runtimes.
- The single speed blower assumption affects the simulation in two ways: the ventilation that is induced through a CFIS system depends on the overall airflow through the system and the duct leakage is considered as a percentage of total airflow (normalized to floor area).
- The assumption that half of total duct leakage is to outside is another over-simplification that does not explicitly account for the interplay between leakage in the belly and heat and (air) mass transfer from the belly back into the living space.
- The method used to estimate the impact of duct leakage and CFIS ventilation is an approximation which assumes that system efficiency is reduced proportional to air leakage or ventilation; the actual impact on run time will vary with many factors, including outdoor air enthalpy and thermal interactions between the belly, into which duct leakage is presumed to most commonly occur, and the living space.
- The airflow induced by the assumed window opening will vary with the orientation of the open windows relative to wind magnitude and direction and the orientation of the home relative to solar insolation, shading and shielding.
- The locations of air leakage pathways are important to the airflows induced by wind and indoor / outdoor temperature differences.
- Heat gains from occupant cooking were not included in the simulation.
- Solar heat gains will vary across homes. We used a single set of shading factors, and at time solar loads were significant. Different shading factors will produce different runtimes.
- There was no explicit accounting for the impact of airflow through open windows on thermal conditions in the home and the secondary impacts on HAC system runtimes. The analysis used a weak coupling of EnergyPlus and CONTAM. Tighter coupling would more accurately capture ventilation related load (and runtime) changes.
- There was no consideration of humidity and water vapor impacts, condensation etc.
- Translating intermittent exhaust airflows (from the dryer and bathroom exhaust fans) that are similar or higher than WHMV into low, continuous airflows results in different overall rates of air exchange and thus different impacts on air pollutant concentrations.

The following specific issues are noted in relation to the impact of variations in key parameters:

- The analysis was conducted only for a single size of “double-wide” or double-section house. The results could differ for other home sizes, in particular for smaller homes that have higher ventilation requirements per square foot of living space because they use the minimum of 50 cfm.
- The assumption that three occupants were always at home does not represent all, or even the majority of U.S. manufactured homes. Those with lower or higher occupancy would have different source and potentially different ventilation characteristics.
- The simulations looked at a single set of temperature set points, specified by location and climate; different temperature set points would result in different amounts of HAC system run time and thus different impacts of air sealing.
- Duct leakage to outside was assumed to be half of the total duct leakage; in real homes this fraction would vary from house-to-house in general, and with environmental conditions for a single house.

- To simplify the model, the HAC recirculating airflow was assumed to be constant for heating and cooling, which is not realistic in many homes. Combination systems of furnace and air conditioning commonly have different airflows in each setting. And many HAC units installed in MH have multiple fan speeds or stages in each mode.
- Among homes that use windows for natural ventilation, the actual usage varies. The scenario of occupants opening windows during every six hour interval of no HAC system operation does not reflect the variability and more complex behaviors that occur in homes even when window opening is routine and aggressive. Actual window use depends on thermal comfort, rain, outdoor air quality, day and night, neighborhood safety etc.
- In addition to home size, thermostat settings, etc. the analysis used discrete values for cooking frequency, emission rates, etc. In reality, all have distributions of values. The overall impacts of air sealing across all manufactured homes would therefore also have distributional values, even if all factors that are not directly related to air tightness remained the same as air tightness is improved.
- Outdoor air contaminants were chosen to be modal values rather than averages. Therefore, the results are informative of magnitudes, not reflective of average conditions or quantitative at a population level.

Of first order relevance to the analysis, the air tightness of HUD Code homes almost certainly varies, with many already being produced with envelope leakage below 8 ACH50 and some or many already at or below 5 ACH50. Air tightness of homes meeting the DOE code would also vary, with many being lower than the nominal limit of 5 ACH50. The distributions, currently and after a rule goes into effect, may not have the same relation to the nominal thresholds. For example, factories that already achieve 5 ACH50 in most of their homes may only have marginal improvements, whereas those with the highest air leakage values could undergo substantial changes in practice to achieve tightness levels substantially below the standard.

The data required to do a distributional analysis, e.g., by Monte Carlo sampling of parameter values, are not available. And if the data were available, the results from such an analysis would be very challenging to digest, given the myriad combinations, e.g., of different mixes of pollutants in homes. The use of discrete values provided a more readily accessible set of results. That said, it is important to note that overall impacts would be different even in the simplified house scenarios studied, if there were different emission rates or mixes of sources for each pollutant.

Another important caveat to the analysis is that there is ample evidence of installed ventilation equipment not providing the airflows that are required by applicable codes and standards, in both site built and manufactured housing. This is true even for the simplest equipment of exhaust fans. For example, in California site-built homes, Stratton et al. (2015) measured 44 bathroom exhaust fans, and found that only 23 met the minimum 50 cfm requirement, largely due to flow restrictions introduced by poorly designed and installed exhaust ducting. In their study of HUD code manufactured homes in MN, Pigg et al. (2016) described other concerns about indoor air quality because of inadequate mechanical ventilation. Site visits found poor bath fan airflow in 52 of the 99 site-visit homes, where the average airflow was only 27 cfm, with about a third of fans moving less than 20 cfm, and one in seven moving less than 5 cfm. For comparison, most bath fans are rated for 50 cfm. They also noted examples of improperly vented bath fan into the attic causing water damage on the ceiling around the bath fan, and non-functioning ventilation equipment.

5 Summary

DOE proposed energy conservation standards for manufactured homes which include improved building envelope insulation values, along with reduced levels of envelope air leakage (assumed to change from a minimum of 8 to 5 ACH_{50}) and reduced duct leakage (from 12 to 4 cfm_{25}/100 sf). Energy modeling by DOE established the potential energy benefits of the proposed rule, along with associated impacts on ambient air quality and household economics. The DOE analysis did not include an assessment of the potential indoor air quality or health impacts of reduced ventilation rates associated with more stringent requirements for envelope and duct leakage in the proposed rule.

To address concerns about potential IAQ impacts, LBNL performed detailed ventilation and IAQ simulations of a standard, double-section MH built to the current HUD code and to the proposed rule. The simulation framework included modeling of thermal loads in EnergyPlus, using adjusted input files from the DOE energy analysis. EnergyPlus outputs for zone temperature, HAC sizing, airflow and runtime were adjusted in post-processing and then passed to CONTAM for airflow network and contaminant modeling. The CONTAM model comprised a single, well-mixed zone for the living space, and two HAC zones (supply and return plenums). The standard MH was simulated in three climate regions, including two HAC types and eight ventilation configurations, with substantial cooking activity. Contaminants included in the simulation were $PM_{2.5}$, formaldehyde, acrolein and NO_2. These contaminants were included because they are routinely found to be above health-relevant thresholds in occupied homes in the US and represent different source characteristics (outdoor, indoor continuous, indoor episodic, etc.). Sources were diverse and distinct for each contaminant, including outdoor air, along with indoor emissions associated with building materials, cooking and non-cooking occupant activities. Ventilation configurations included three whole house mechanical ventilation types (continuous exhaust fan, and both continuous and runtime CFIS supply ventilation), along with variations in the use of operable windows and local exhaust fans in the kitchen and bathrooms. All cases included a small increment of continuous airflow to estimate the impact of intermittent use of a vented clothes dryer.

The analysis found that the proposed rule would lead to reductions in outside air ventilation rates in all cases assessed, with typical reductions of around 25–30% for continuous exhaust systems and around 40% for CFIS supply systems, either operating continuously or only when the heating or cooling system operated. When the simulations considered window opening during any 6 hour period that the heating and cooling system did not operate, the changes to annual average AER were smaller, 13–15% in Fresno and Houston but 25% in Chicago.

6 Conclusions

The purpose of this analysis was to inform the Environmental Impact Statement (EIS) for the DOE proposed rule. The results of this analysis are presented in that EIS along with discussion of existing conditions (i.e., air pollutant concentrations currently in homes) and the implications of the estimated changes in air pollutant concentrations to health risk. Interested readers are referred to the full EIS for these discussions, as well as additional information about the impacts of the proposed rule. A summary and links to the Draft and Final EIS are available at this site:

https://www.energy.gov/nepa/doeeis-0550-energy-conservation-standards-manufactured-housing

The citation and direct link are as follows:

Final Environmental Impact Statement for Proposed Energy Conservation Standards for Manufactured Housing. DOE/EIS-0550D. [Link]

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