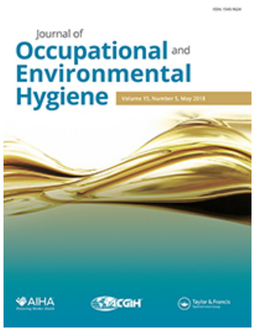

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://oeh.tandfonline.com/loi/uoeh20

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**To cite this article:** Michael Jayjock & Andrew Anthony Havics (2018) Residential inter-zonal ventilation rates for exposure modeling, Journal of Occupational and Environmental Hygiene, 15:5, 376-388, DOI: 10.1080/15459624.2018.1438615

**To link to this article:** https://doi.org/10.1080/15459624.2018.1438615

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2018, VOL. 15, NO. 5, 376–388
https://doi.org/10.1080/15459624.2018.1438615

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# Residential inter-zonal ventilation rates for exposure modeling

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ABSTRACT

Residential inter-zonal (e.g., between rooms) ventilation is comprised of fresh air infiltration in and exfiltration out of the whole house plus the "fresh" air that is entering (and exiting) the room of interest from other rooms or areas within the house. Clearly, the inter-zone ventilation rate in any room of interest will be greater than the infiltration/exfiltration ventilation rate of outdoor air for the whole house. The purpose of this study is to determine how much greater the inter-zonal ventilation rate is in typical U.S. residences compared to the whole house ventilation rate from outdoor air. The data for this statistical analysis came from HouseDB, a 1995 EPA database of residential ventilation rates. Analytical results indicate that a lognormal distribution provides the best fit to the data. Lognormal probability distribution functions (PDFs) are provided for various inter-zonal ventilation rates for comparison to the PDF for the whole house ventilation rates. All ventilation rates are expressed as air change rates per hour (ACH). These PDFs can be used as inputs to exposure models. This analysis suggests that if one were performing a deterministic analysis for unknown housing stocks in the U.S., a default mean and median ACH values of 0.4/hr and 0.3/hr, respectively, for whole house ventilation would be appropriate; and 0.7/hr and 0.6/hr, respectively, for inter-zonal ventilation.

KEYWORDS
ACH; air exchange; exposure; inter-zonal; model; ventilation

## Introduction

Air exchange rates have been important factors for both assessing energy usage and evaluating indoor exposure to pollutants, particles or consumer products[1–7] and for design of thermal comfort and proper air quality.[8] Quantification of whole building infiltration rates is not enough to properly characterize indoor air quality and energy consumption.[3] In the case of indoor exposure, the primary focus has been on inhalation exposure. Inhalation exposure assessment typically derives from the evaluation of the concentration of a toxicant or toxicants in the breathing zone (BZ) of a person. This BZ concentration, in-turn, is either measured directly or estimated using models. This work deals with a critical element in the modeled estimation of airborne concentrations of toxicants indoors in residences; namely, it examines the ventilation rate. Indeed, essentially all physical-chemical inhalation exposure models need to account for the amount of toxicant entering a room (or volume) of interest and the mechanisms in place to remove the toxicant from the air. Ventilation represents the primary and, in most cases, the only mechanism considered for removal of the airborne toxicant. Thus, the accurate assessment or estimate of ventilation in any indoor environment could be critical to the accuracy of the overall modeled exposure and subsequent risk assessment from inhalation exposure. Often, a point estimate of an exchange rate is desired,[9] however, this study has also produced distributions of exchange rates.

## Background on housing and air exchange rates

Free-standing and row residential homes typically do not have provisions for positive outdoor air input to interior spaces; that is, there are no fans drawing air directly into the interior volume through ducts as ASHRAE 62.1 (Ventilation for Acceptable Indoor Air Quality) and ASHRAE Standard 62.2 (Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings – Building America Top Innovation) have historically presumed that infiltration (natural, or induced by supply fans, or induced by exhaust fans) would supply this outdoor air. Thus, essentially all free-standing and row homes receive their outdoor air via infiltration through the cracks and other incidental openings in a process that is driving by wind speed and the "chimney effect" propelled by the differences in temperature between indoors and outside.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uoeh.

Energy-efficient homes, because of superior insulation and sealing, have less ventilation of outside air than older homes which are often considered "drafty." All homes, however, have (and need) some level of infiltration of outdoor air. In addition, most homes in the U.S. have central HVAC systems, which tend to mix the air, and thus, the indoor conditions between zones.[10] The effectiveness of a given mechanical ventilation system will depend on airflows between each zone as well as flows to and from outside.[10]

To arrive at an accurate estimate of the amount of ventilation in an entire residence one needs to account for all the air entering and leaving that residence from the outside. As a general rule, these rates are equal. That is, in any reasonable time frame, the amount of air going into any house or any room within the house will equal the amount leaving, otherwise the room or house would overpressure or a vacuum would be created.

The amount of air entering (infiltrating) or exiting (exfiltrating) a free-standing or row home is typically described by the net volume of such air per unit time divided by the volume of the house:

$$ACH = \frac{Q}{V} \tag{1}$$

ACH = air changes per hour (1/hr)
Q = rate of air coming in or leaving the home ($m^3$/hr)
V = volume of the house ($m^3$)

To address the question at hand, that is, to arrive at an accurate estimate of the amount of ventilation in *any room of interest* one needs to account for all the air entering and exiting that particular room. For rooms with exterior walls, this includes outdoor air infiltration/exfiltration plus air entering and exiting from adjacent rooms. This total flow is the inter-zone ventilation and is obviously greater than just the fresh air exchange of outdoor air.

Inter-zonal ventilation is expected to be quite different between houses that have forced air high volume air conditioning (HVAC) systems [active] and those with radiant heating [passive] as a mechanical ventilation technique provides an additional force driving air movement. Many, if not most, newer houses have HVAC systems with central fans within a ducted system that purposely recirculates air within the system when they are on. Older houses typically do not have a duct system and rely on radiant heat with the possible and selected addition of localized fans or room air conditioning in window units.

Inter-zonal ventilation would be less important to the evaluation of general sources of toxicants spread throughout the home. Examples would be a house that had new carpeting installed throughout or a house that was built with contaminated wallboard throughout the building. Here, the general ventilation from outdoor air would be sufficient to support the modeling effort. Scenarios where an accurate estimate of inter-zonal ventilation would be critical would be in the evaluation of exposure from a single source isolated within a single room or strong spatial differences of sources or sinks between zones. Here relatively fresh air from adjacent rooms would effectively add to the overall ventilation rate controlling this source.

The importance of inter-zone exchange rates occurs in various ways: it was found to have a greater effect than zone volume on concentrations,[11] rates could account for different concentration ranges in buildings with similar whole building exchange rates,[11] inter-zone ventilation rate was the most important parameter in Near-field exposure to consumer products,[12] was considered a possible cause of the personal cloud compartmental effect in personal vs. area sampling;[13] rates can assist in quantitatively evaluating mechanical ventilation contribution to air exchange rates,[14] rates can be used to evaluate source-sink location effects,[15] rates allow for quantification of $NO_2$, and radon transport and fate.[16]

Work on multi-zone exchange rates have been investigated since at least since 1949 where the term coupling was used to described inter-zonal transport,[17] with the first zonal model system devised in 1970.[18,19] The evaluation of infectious agent transport in hospitals,[20–22] and more generally interzonal investigations, whether actual or modeled, regarding energy loads and contaminant fate and transport have been completed for small and large one-story and multi-story commercial and industrial buildings.[23–27] These are not representative of residential housing stock, although they can provide information regarding the factors, assumptions, and limitations in assessing inter-zonal exchange rates as discussed below. Furthermore, the use of inter-zonal exchange rates have been demonstrated as essential in assessing exposure to smoke, VOCs, biochemicals, viruses and bacteria, methylene chloride in aerosol paint, diethylene glycol monobutyl ether release in paint, carbon monoxide release, para-dichlorobenzene release from moth balls, perc from dry cleaning clothes, and others.[15,20,21,28–36]

## Methods

Perhaps the best way to evaluate inter-zonal ventilation in U.S. homes is to begin with reasonably contemporary measured data for this variable in a representative number of homes. There have been limited singular studies with data on inter-zonal exchange rates for simple or singular rooms, kitchens, roofs/attics, basements, garages, test houses,[2,4–6,9,10,13,15,16,33,36–47] or modeling only,[3,23,30,31,48] but not for multiple buildings sufficient to generate group-based statistics.

Thus, we began by consulting with Dr. Andrew K. Persily of the National Institute of Standards & Technology (NIST) on the best source for the data; Dr. Persily has been engaged since the late 1970s in the development and application of measurement techniques to evaluate airflows and indoor air contaminant levels in a variety of building types, including large, mechanically ventilated buildings and single-family dwellings. He advised that the Lawrence Berkeley Laboratory had a large database of residential airtightness measurements, but that it did not include inter-zone airflow rates.[49]

One recent study in the U.S.[50] examined 126 predominantly low income African American and Latino households in Detroit, Michigan to characterize the ACH in whole houses and inter-zonal ACH flow in and out of bedrooms. They reported an all-season interquartile range of ACH of 0.32–0.90 for the whole house and a concurrent interquartile range of 0.68–2.07 ACH for bedrooms in the study. The majority of homes in this study (88%) used forced air heating systems. The authors suggested that the relatively high rates of ACH ventilation for bedrooms suggest that windows were frequently open during measurement or that the bedrooms were relatively "leaky." In any event the housing stock used in this study was somewhat limited as was the geographical location and type of heating used.

Similarly, Dodson[51] provided interzonal data between residence occupied spaces and garages or basements. However, they only did so for 45 residences in the Boston area and only provided air flows in volumetric values except for an overall average inter-zonal rate for all residences of 1.1 ACH. Shinohara[52] presented whole residence and inter-zonal ACH data from 26 residential buildings in Japan. He reported all-season ranges of 0.38–1.4 ACH for whole residence and 0.42–1.6 ACH for inter-zone rates. He noted inter-residence variability much higher than daily and seasonal intra-residence variability. Beko[53,54] provided data on bedroom exchange rates which were effectively complete singular inter-zone rates in 500 Danish residences. Mean, median, and geometric mean values for all 500 bedrooms were reported as 0.62, 0.43, and 0.46 ACH, respectively. Beko[55] also provided inter-zonal data on a separate 5 residential buildings in Denmark which had all-seasonal averages of 0.36–1.67 ACH. The mean ACH measured in children's bedrooms of single family homes in Sweden ranged from 0.31–0.47 ($n = 390$), and depended on the ventilation system, construction period, foundation type and number of floors.[56] These were useful, but insufficient to provide a broader-based dataset for a greater representation of the U.S. housing stock.

Fortunately, we have the HouseDB database created by EPA, which appears to offer very useful data for this analysis. The HouseDB database was built into the EPA Multi-chamber Concentration and Exposure Model (MCCEM).[57] It appears to be somewhat unique in that it includes 603 data sets of actual multiple tracer gas measurements of real homes in which the whole house ACH was measured and matched with balanced inward and outward air flows for what it termed was interior Zone 1, Zone 2, and Zone 3 within the house. Zone 0 was designated as the space outside the house. The interior residential zones (1–3) were often described as rooms (e.g., bedroom, kitchen) or larger areas or segments of the house like upstairs or basement. The houses tested included data from various states across the U.S. and presumably represent a cross-section of U.S. housing stock and heating conditions including radiant and mechanical HVAC systems at the time of the study, which was published in 1995. The details of this multiple tracer gas study of real homes completed by Geomet are available as a report[58] and drawn upon in summary form for the EPA's Exposure Handbook,[59]

Briefly, the multiple tracer gas technique allows investigators to address multiple zones indoors by using a constant rate emitting source of different tracer gases in each zone.[16,38,42] This is done until the concentration of each tracer reaches a steady-state in each zone as which point the concentrations are measured. This allows for the calculation of the infiltration and exfiltration of outdoor air for each zone of the house as well as the flows between zones. All of these data points and parameters were included in the HouseDB database.

The authors of HouseDB have pointed out several factors affecting variability, bias, and accuracy, or ones that limit proper application of tracer data for exchange rates estimation. These include: vertical and horizontal spatial positioning, mixing effects, wind effects, regional variation, season effects, barometric pressure, temperature gradients, whole volume (capacitance) effects, tracer diffusivity, tracer confounding sources, openings sizes and types between zones, intra- and inter-day variation, uniform pressure field or uniform total pressure field, sampling rate/interval, and constant airflow rates.[1,4,5,7,17–19,47,48,60–85] A few measures, described below, were used to limit the variability in the final output data. In spite of the remaining imitations, the bias and mean error are expected to be in the range of $<20\%$ (based on variable flow effects) with some exceptions up to approximately 25% for deterministic bias.[1] In addition, seasonal measurements by single tracer may under predict average exchange rates by 20–30% whereas multiple tracers (as used in the data applied in this study) can reduce uncertainty to 10–20% of the zone total rate.[58] As mentioned above, the HouseDB database is built into the EPA's MCCEM program. Indeed, Michael Koontz, noted that the housedb.dbf file is unzipped and extracted into the MCCEM directory when that program is installed on a PC. Unfortunately, installing and running the old IBM-PC version of MCCEM is not compatible with any version of Windows after Windows 7. Thus, as a convenience, the Housedb.dbf files and its converted version (Microsoft Excel) are available as supplemental online files.

Given the presumed diversity of this database relative to geographical location in the U.S., age and heating system types, we anticipated a fairly broad distribution of fresh air and inter-zonal airflows and ventilation. One would anticipate that higher inter-zonal ACH levels could result in newer homes with HVAC central fans and lower levels of inter-zonal ACH in homes with radiant heating. Working against this assumption is the distinct probability that older homes are less well sealed and therefore might have relatively high infiltration ACH levels. In any case, using this diverse database of measured values was expected to allow one to produce and analyze the entire range of whole house and inter-zonal ACHs as probability distribution functions (PDFs), not just discrete point estimates. These PDFs could be used to facilitate a Monte Carlo uncertainty analysis or provide a reasoned choice of deterministic values of ventilation for rational average case or worst-case modeling.

The ultimate aim was to examine the distribution of reasonable worst-case conditions of indoor inter-zonal ventilation in situations where the exterior doors and windows would be closed. This would reduce variability as well. To do this we chose only values taken in winter and eliminated values from the only 2 often warm-weather states in the database of California and Texas. These eliminations of seasons and states left a database of 175 homes in which one exterior zone (Zone 0) and at least 2 interior house zones (Zone 1 and Zone 2) were measured.

The HouseDB database presents total and balanced air-flow rates in and out of Zone 0 (outdoors) and Zone 1, Zone 2, and Zone 3 measured indoor volumes. That is, within this database every zone is considered to be adjacent to, and exchanging air with, every other zone inside and out of the house. For example, in a house that had 3 measured interior zones (remembering that Zone 0 is the outside) the following 12 (in and out) zonal flows were estimated simultaneously using multiple tracer gases:

Zone 0 to Zone 1
Zone 0 to Zone 2
Zone 0 to Zone 3
Zone 1 to Zone 0
Zone 1 to Zone 2
Zone 1 to Zone 3
Zone 2 to Zone 0
Zone 2 to Zone 1
Zone 2 to Zone 3
Zone 3 to Zone 0
Zone 3 to Zone 1
Zone 3 to Zone 2

Please note that the above reciprocal flows are typically not equal. That is, the Zone 1 to Zone 0 flow does not typically equal the Zone 0 to Zone 1 flow. Only the *total* flow in and out of each zone has to be equal and balanced, under the assumption of a pressure balanced system (which is expected to be sufficiently valid over the time periods anticipated in exposure assessments).

For a house with two measured interior zones the following six (in and out) flows were measured:

Zone 0 to Zone 1
Zone 0 to Zone 2
Zone 1 to Zone 0
Zone 1 to Zone 2
Zone 2 to Zone 0
Zone 2 to Zone 1

Air entering any house is called infiltration. Infiltration is quantified here as the total air flow into the house to all Zones from Zone 0 while the balanced total flow out of all Zones to Zone 0 is exfiltration. There were 175 sets of entries for individual flow into and out of Zone 0, 1, and 2 and 17 of these entries that included individual flows for Zones 0, 1, 2, and 3.

The original HouseDB file (housedb.dbf) was first transferred to Microsoft Access and then exported to a Microsoft Excel file. As mentioned above, all entries not in winter and all entries from California and Texas were eliminated leaving 175 data sets. The spreadsheet contains the basic flow data which was used to calculate the total/balanced air-flow rates for each zone. The individual zone volumes reported in the database for each zone were used to calculate the air exchange rate (ACH) for each zone separately within the spreadsheet.

Each calculated ACH for each zone was then considered in a distributional dataset for that zone. There were 175 entries each for Zone 0, 1, and 2 with 17 entries in the dataset for Zone 3. The spreadsheet for the dataset (HouseDB WIN minus CA TX.xlsx) is included in the online supplemental material. Also included as supplemental online material is a more user-friendly version of the spreadsheet supplied by Daniel Drolet (Daniel CB HouseDB Win minus CA TX.xlsx).

Oracle Crystal Ball[86] was used to first fit each of the above ACH datasets to 13 probability distributions (PDFs): Lognormal, Normal, Weibull, Exponential, Gamma, Pareto, Beta, BetaPERT, Max Extreme, Student's t, Min Extreme, Triangular, and Uniform. After fitting, a goodness of fit ranking was done by Anderson-Darling, Kolmogorov-Smirnov (K-S), and Chi-Square tests for each distribution.[87,88] For the choice of which ranking tool to use, the Oracle Crystal Ball documentation[86] provides the following guidance.

In ranking the distributions, you can use one of three standard goodness-of-fit tests.

- **Anderson-Darling (A-D)** — This method closely resembles the Kolmogorov-Smirnov method, except that it weights the differences between the two distributions at their tails greater than at their mid-ranges. This weighting of the tails helps to correct the Kolmogorov-Smirnov method's tendency to over-emphasize discrepancies in the central region.
- **Kolmogorov-Smirnov (K-S)** — The result of this test is essentially the largest vertical distance between the two cumulative distributions.
- **Chi-Square** — This test is the oldest and most common of the goodness-of-fit tests. It gauges the general accuracy of the fit. The test breaks down the distribution into areas of equal probability and compares the data points within each area to the number of expected data points.

The Anderson-Darling (A-D) method was chosen as the predominant method, and is recognized as being very predictive;[88] however, since all three were calculated all are listed below. Results for the fitted distribution providing the best goodness-of-fit with p-values and the next best fitting distribution with p-values are presented in the results section (Figures 1–4).

The chosen best fit probability distribution of ACH for each zone was then plotted for Zone 0 (total air flow in and out of house), Zone 1, Zone 2, and where available, Zone 3. These are presented in Figures 1–4.

## Results

For the 52 fitted distributions in this study (13 distributions fit to datasets for 4 zones) the lognormal PDF was *always* the best fit to each dataset analyzed. Note the p-values for the goodness of fit methods tests the hypothesis that the data fit the distribution. The statistical tests used here *rejects the hypothesis of a good fit when the p-value is less than or equal to 0.05.* Failing the fit test ($p \leq 0.05$) allows one to state with 95% confidence the data does not fit the tested distribution. Details of the fit data are provided in Appendix A. Figures 1–4 present the PDFs for the best-fitting lognormal distribution.

In addition to histograms of whole house and inter-zonal exchange rates, the ratio of inter-zonal rates of

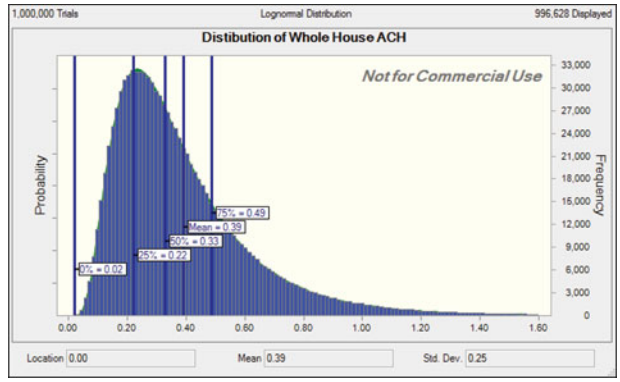


**Figure 1.** Zone 0 or Whole House ACH (Winter). **Passed A-D fit test ($p = 0.185$)**: Arithmetic Mean = 0.39; Arithmetic Std Dev. = 0.25; Geometric Mean = 0.33; Geometric Standard Deviation (GSD) = 1.80.

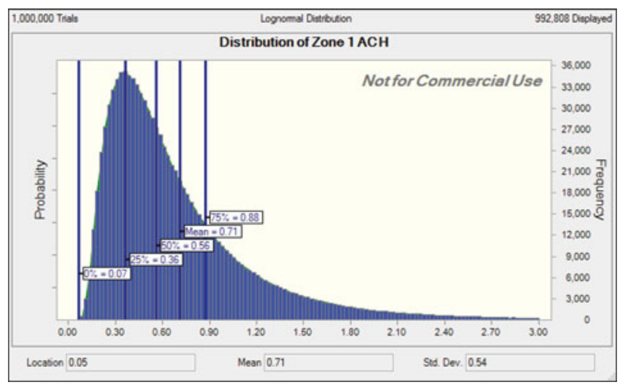


**Figure 2.** Zone 1 ACH (Winter). **Passed A-D fit test ($p = 0.828$)**: Arithmetic Mean = 0.71; Arithmetic Std Dev. = 0.54; Geometric Mean = 0.51; Geometric Standard Deviation (GSD) = 2.05.

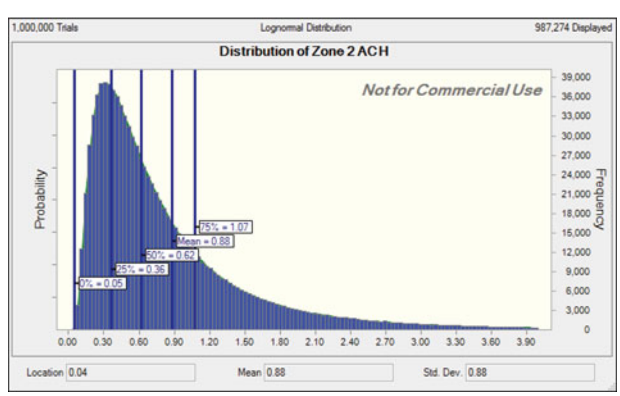


**Figure 3.** Zone 2 ACH (Winter). **Failed A-D fit test ($p = 0.028$)**: Arithmetic Mean = 0.88; Arithmetic Std Dev. = 0.88; Geometric Mean = 0.58; Geometric Standard Deviation (GSD) = 2.36.

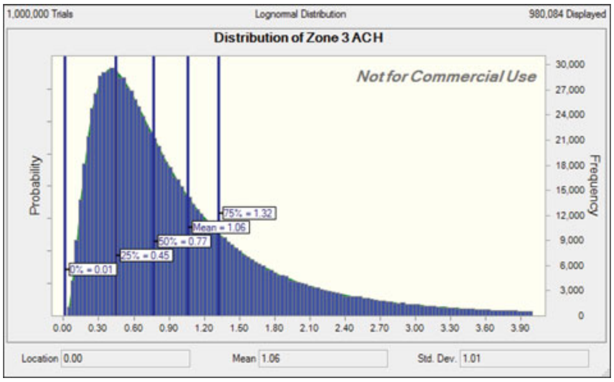


**Figure 4.** Zone 3 ACH (Winter). **Passed A-D fit test: p = 0.079**: Arithmetic Mean = 1.06; Arithmetic Std Dev. = 1.01; Geometric Mean = 0.77; Geometric Standard Deviation (GSD) = 2.23.

Zones 1 and 2 to the whole-house rate was calculated. The results are presented in Figures 5 and 6. The statistical results for these ratios are presented in Table 1.

**Table 1.** Inter-zone to whole house exchange rate ratios.

| Inter-zone | N | 10% Quantile | Median | Geometric Mean | Arithmetic Mean | 90% Quantile |
|---|---|---|---|---|---|---|
| 1 | 175 | 0.91 | 1.78 | 1.694 | 1.89 | 2.91 |
| 2 | 175 | 1.15 | 1.79 | 1.906 | 2.31 | 3.55 |

## Discussion

It is interesting to note that the best fit of the ventilation rate data to the lognormal distribution occurred for the total house ACH (Zone 0) and the inter-zonal ACH in Zone 1. The Zone 0 or whole house infiltration/exfiltration ACH distribution calculated in this work is comparable to previous studies in terms of being skewed or Lognormal.[16,89–93] Although the distribution is lognormal, modeling suggests that using a fixed value with Gaussian noise as an input in a two-zone model produces a normal (Gaussian) inter-zonal output distribution under various conditions.[82] This suggests a few

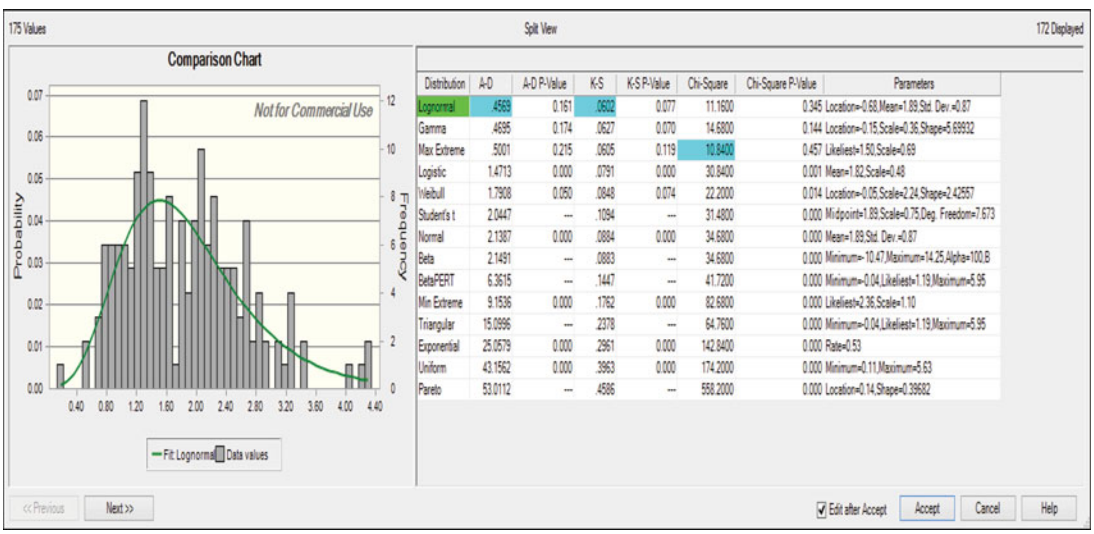


**Figure 5.** Ratio of inter-zonal rates for Zone 1 to whole-house rates.

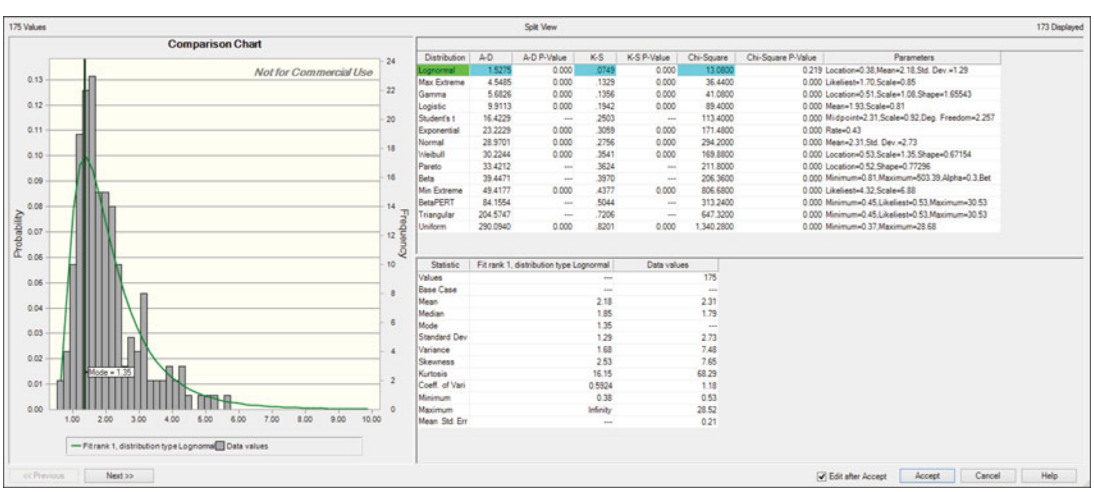


**Figure 6.** Ratio of inter-zonal rates for Zone 2 to whole-house rates.

**Table 2.** Comparison of seasonal whole house exchange rates.

| Climate Region | Season | n | Arithmetic Mean | Std Dev | 50th Percentile | 75th Percentile | 90th Percentile |
|---|---|---|---|---|---|---|---|
| THIS STUDY (HouseDB) | Winter | 175 | 0.39 | 0.25 | 0.33 | 0.49 | 0.70 |
| Coldest | Winter | 161 | 0.36 | 0.28 | 0.27 | 0.48 | 0.71 |
| Colder | Winter | 428 | 0.57 | 0.43 | 0.42 | 0.69 | 1.18 |
| Warmer | Winter | 96 | 0.47 | 0.40 | 0.39 | 0.58 | 0.78 |
| Warmest | Winter | 454 | 0.63 | 0.52 | 0.48 | 0.78 | 1.13 |

NB: The coldest region was defined as having 7,000 or more heating degree days, the colder region as 5,500–6,999 degree days, the warmer region as 2,500–5,499 degree days, and the warmest region as fewer than 2,500 degree days.

**Table 3.** Zone Z /Zone 0 (outside) flows and exchange rates.

| Stat Parameter | Basement Avg Flow | Basement ACH | Bedroom Avg Flow | Bedroom ACH | Rec Room Avg Flow | Rec Room ACH | Dining Rm Avg Flow | Dining Rm ACH |
|---|---|---|---|---|---|---|---|---|
| Average | 89.17 | 0.52 | 43.27 | 0.48 | 117.24 | 0.30 | 133.5 | 0.53 |
| Standard deviation | 57.83 | 0.45 | 15.77 | 0.34 | 49.42 | 0.11 | NA | NA |
| Minimum | 5.20 | 0.03 | 24.05 | 0.16 | 34.60 | 0.15 | 133.5 | 0.53 |
| Maximum | 287.95 | 2.68 | 58.95 | 0.94 | 203.80 | 0.51 | 133.5 | 0.53 |
| n | 110 | 110 | 4 | 4 | 8 | 8 | 1 | 1 |

causative options in need of further investigation: (a) that source inputs/sinks, or frequency of pulsed inputs/sinks, is lognormal, or at least non-normal; (b) the housing stock is constructed such that natural infiltration factors are non-normally distributed; and (c) the mechanical ventilation system operate in a non-normal manner. It is also interesting to note that many environmental exposure sampling sets have been found to be lognormally distributed,[94–97] with varying suggestions as to why.[98–100]

The EPA Exposure Factors Handbook[59] contains summary data from an extensive study of the infiltration ACH of U.S. homes.[91,93] The Murray and Burmaster distributional data is compared to the whole house ACH data from this study[59] in Table 2.

The data demonstrate consistency for at least the whole house in the winter months. This suggests that this study's data is (a) valid in terms of its range of housing stock and (b) may be used to predict inter-zonal rates in other housing by using the ratios of the whole house and inter-zonal exchange rates. The validity of this study's data is also supported by comparison to a residential energy consumption survey, which included 140 single-family houses in 19 cities, that showed a median (50$^{th}$ percentile) whole house ACH of 0.44 with a range from 0.26–0.58 ACH.[101]

The *EPA User Manual* for its RISK software[102] states the following general conclusions regarding whole house ACH: In general, reasonable values of air exchange between the indoors and outdoors are:

0.3 for tight construction,
0.5 for typical energy efficient construction and
1.0 for construction over 30 years old.

The above data from the Murray and Burmaster and Persily[91,101] suggest that these estimates may be slightly high, and may either overestimate indoor-to-outdoor transport of contaminants (and thus overestimate exposure from outdoor sources), or underestimate exposure indoor-to-outdoor transport (and thus underestimate exposure from indoor sources).

Relative to the inter-zonal ACH PDFs from this study Zone 1 and Zone 3 passed the fit test for the lognormal distribution; however, Zone 1 had the best fit (highest p value) and the most data points (175 vs. 17). In addition to a better fit, the fitted lognormal distribution for Zone 1 had a lower mean and smaller standard deviation than the fitted lognormal distributions for Zones 2 and 3. As such, the PDF for Zone 1 will be used for subsequent analysis. It should be mentioned, however, that the distributions for Zones 2 and 3, while being somewhat higher and wider, are not dramatically different from that of Zone 1.

It is interesting to note that the tail of the fitted Zone 1 distribution for inter-zonal flow runs out to about 3 ACH which is comparable to the minimum inter-zonal ACH indicated on p.140 of the *User Manual* for the EPA Program RISK Version 1.5.[102] Reportedly, this is from EPA test house experiments. Unfortunately, this document does not appear to available from the EPA online. We have included it as supplemental material for this article.

Given the EPA data and analysis, some investigators have estimated and used an inter-zonal ACH of 3.5/hr or 3–6/hr when modeling exposure.[103,104] It would appear that 3–3.5 is a reasonable estimate of inter-zonal ACH when the HVAC central fan is running. Indeed, Dr. Persily has advised that an inter-zonal ACH of 3.5/hr is "a good order of magnitude estimate for the airflow associated with a forced air system."[49] He also notes that the central fans do not run 100% of the time but only when the thermostat declares the need for heating or cooling. He further comments that residential heating and cooling systems are often oversized for a variety of reasons, which means they can run only fraction of the time unless it's very hot or very cold outside.[49] In Europe, low ACH inter-zonal ventilation rates have been reported in bedrooms as indicated above in earlier studies usually with a median/mean about 0.3–0.5 ACH.[53,55,56]

The results also indicate, as expected, that the inter-zonal exchange rates significantly exceed the hole-house rates as observed in the typical ratios of inter-Zones 1 & 2 compared the whole house rate. The results suggest that in cases where an inter-zonal estimate is desired that one can estimate the inter-zonal rate as being in the range of the mean/median at approximately 1.8–1.9 times the whole house rate. For example, if one is modeling the exposure in two separate zones during smoking or painting in one zone, but not the other, and one has a whole house exchange rate of 1.25 ACH. One can use a 2-zone model with an inter-zonal rate estimate of 2.25–2.375 ACH (1.8–1.9 times 1.25). If other ranges are desired, 10–90%, these too could be used in the model.

It is beneficial to consider the inter-zone ACH rates discussed here compared with other authors' representations to both understand their potential application as well as recognize differences in terminology. To begin with, using assumptions of constant source, sink, and air flow terms, Sparks[105] showed in a multi-room model that the concentration ($C_i$) in a room *i* at some time *t* could be represented by the equation:

$$Ci = COe^{-(Li)t} + \frac{Pi}{Li}\left(1 - e^{(Li)t}\right), \qquad (2)$$

C0 is the concentration in room i at the start time ($t_0$), Li is the inter-zonal ACH out of the room, summed from all flow components, Pi is the inter-zonal ACH into of the room, again as summed from all flow components multiplied by the local concentration plus any sink or source mass values.

In a comparable fashion using matrices, Sandberg[106] provided an in depth evaluation of multi-cell modeling representing the inter-zonal ACH with the matrix $\tau^{-1}$, where each term in the matrix is an one-way interzonal rate. Jacques[107] uses the same matrices basis (albeit using the actual Q and V terms) to evaluate multi-room contaminate concentrations. Sandberg goes further and demonstrates the effect of inter-zonal ACH on various aspects of the model in terms of physical constraints and mathematical operations. Parker[11] evaluated a contaminant time series using the matrix A instead of $\tau^{-1}$. He applied this to a two-zone building model wherein there is an inner protected Zone 2 that does not communication with the outdoor (Zone 0) air directly, but only through the building Zone 1. This is in essence a classical two-zone Near-field/Far-field (NF/FF) model described in AIHA's Mathematical Models for Estimating Occupational Exposure to Chemicals.[108] In the NF/FF model, the parameters $\lambda_1$ and $\lambda_2$ are used to describe values that approximate what are termed Far-field and Near-field air turnover rates; the Near-field term being designated as beta/Near-field Volume ($\beta/V_N$), hence an air exchange rate. Others have referred to this $\beta$ as an inter-zone flow or inter-zone flux and the term $\beta/V_N$ as an inter-zonal air exchange rate.[109–113] It is important to note that this inter-zonal rate is *not* the same as that which we have described. The Near-field ($\beta/V_N$) term for the air exchange rate is used with a Far-field exchange rate (Q/VF) to effect the Near-field concentration. There is no comparable direct inter-zonal rate to account for a direct exchange between the Near-field and the outside, e.g., Zone 0 to Zone 2 and Zone 2 to Zone 0 airflows are zero or non-existent. This is the same as Parker's inner protected Zone 2 model. Thus, the inter-zonal data provided here should not be used in the NF/FF model without proper consideration of the need for adjustment, e.g., without developing a proper relationship between Near-field ($\beta/V_N$) term and our inter-zonal term.

To evaluate the contribution of the direct communication between the isolated zone such as a Near-field type approach and the outdoor air (Zone 0), we extracted portions of the data for specific types of zones. These were basements and cellars, single bedrooms, recreational rooms, and a dining room; we referred to these as Zone Z. We presumed these had the most potential for being isolated from Zone 0 (outdoor air) and thus representative of an isolated Near-field space. Because the flow from Zone Z to Zone 0 and the reverse flow from Zone 0 to Zone Z are generally not equal, we calculated an arithmetic average flow. This was then used to calculate a Zone 0–Z air exchange rate by dividing by the volume of Zone Z, with the results presented in Table 3. Although the ranges are great, the bulk of the values are in around 0.5 ACH. This finding is unexpected as one would surmise that most basements would have little communication with outdoor air as they would be mostly surrounded by soil and be at or below 0.1 ACH. The other rooms could have direct communication with outdoor air as descriptions in the database were not sufficient to ferret out exact spatial relationships. In light of this finding, it may be appropriate to use the ACH rates herein for $\beta$ values in a NF-FF model for residential housing. Given construction and operational differences between residential and commercial or industrial buildings, we would not recommend using these inter-zonal rates for anything but residential stock housing.

Furthermore, one could use a finite element type multi-cell approach, such as that used by Buringh[114,115] in an industrial application, with inter-zonal rates used across discrete boundaries (blocks of cells between zones) provided the time steps are on the order of the exchange rates. It is important to recognize that there can be substantial differences of indoor concentrations depending on whether a single zone (e.g., one room) or a two-zone (e.g., two room) approach is used. Evans[23] details just such an example using a consumer applied spray product on a mass basis with an ACH around 1–2. The results show that (a) the two-room masses in the source area are always less than the one-room model, and (b) the peak mass in the source room compared to the non-source room is in the range of two- to three-fold higher depending on the emission pattern.

## Conclusions

The HouseDB database used in this analysis provides a unique, robust, and broad-based *measured* dataset to estimate the distribution of *both* whole house and inter-zonal air exchange rates in U.S. houses. These measurements were taken in a cross-section of U.S. housing stocks and locations within the country and the whole house data agrees reasonably well with other comprehensive U.S. studies of whole house ACH.

Analysis of the HouseDB data set provides a PDF (Zone 1) that should be useful in exposure models requiring inter-zonal ventilation; namely, scenarios in which a source is isolated to a single room within the house. One can use the Zone 1 PDF directly in a Monte Carlo simulation or select values from it for an average or typical worst-case evaluation. If single values are needed, the Zone 1 PDF median value of 0.7/hr inter-zonal ACH would appear to be a reasonable value to use in indoor models for the above scenario types. Worst case could be 0.4/hr or the 25$^{th}$ percentile value.

The above inter-zonal PDF is compared to the whole house (Zone 0) PDF which shows less ventilation with a median Zone 0 PDF value of 0.4/hr. The whole house (Zone 0) PDF is appropriately applied to modeling exposures from sources occurring throughout the entire house. Worst case could be 0.2/hr or the 25$^{th}$ percentile value of the Zone 0 PDF.

Alternatively, if something more is known about the PDF or range of the whole house exchange rate (s) for a single or subset of houses, one can apply a ratio (inter-zone:whole house) factor to the PDF (or range) to provide a more case-specific estimate of an inter-zonal exchange rate. This set of inter-zonal exchange rate PDFs may also permit further evaluation of discrepancies in exposure samples to account for inter-zonal fate and transport of pollutants; for example, differences in particle or vapor concentrations, or variations caused by activities generating resuspensions. It may also be used to assist in exposure estimates of selected zone application or release of consumer products (e.g., cigarettes, cannabis combustion products, perfumes, paints, building product application.) or restricted use products (e.g., pesticides, refrigerants, fire suppression agents, pharmaceuticals) prior to their use, or even post hoc after an accident, or naturally occurring allergens (e.g., dog/cat dander, mite allergen, pollen, mold).

## Acknowledgments

Many thanks to Andrew Persily, Michael Koontz, Jeniffer Sahmel, and Daniel Drolet for their data, conversations, papers, and collective knowledge.

## Funding

The authors and contributors performed this work without funding.

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## Appendix

Data: **Winter** Inter-zonal and whole house ventilation rates expressed as mixing air changes per hour (ACH) reported in HouseDB database **minus** all entries from California and Texas.

### GOODNESS-OF-FIT STATISTICS

| | | | | | | |
|---|---|---|---|---|---|---|
| **Zone 0 (whole house ACH) 175 data points**: | | | | | | |
| Distribution | A-D | A-D **p-Value** | K-S | K-S **p-Value** | Chi-Square | Chi-Square **p-Value** |
| **Lognormal** | .4447 | **0.185** | .0504 | **0.256** | 8.7600 | **0.555** |
| Lognormal Parameters for Zone 0 (whole house) **Location = 0.00, Mean = 0.39, Std. Dev. = 0.25** | | | | | | |
| Next best fit: | | | | | | |
| Gamma | .6265 | 0.098 | .0562 | 0.213 | 10.0400 | 0.437 |
| **Zone 1 (Total Inter-zonal ACH) 175 data points**: | | | | | | |
| Forecast: Data Analysis: | | | | | | |
| *Anderson-Darling | | | | | | |
| Distribution | A-D | A-D **p-Value** | K-S | K-S **p-Value** | Chi-Square | Chi-Square **p-Value** |
| Lognormal | .1992 | **0.828** | .0396 | **0.595** | 13.0800 | **0.219** |
| Lognormal Parameters for Zone 1 lognormal fit: **Location = −0.05, Mean = 0.71, Std. Dev. = 0.54** | | | | | | |
| Next best fit: | | | | | | |
| Gamma | .4758 | 0.228 | .0534 | 0.281 | 19.3200 | 0.036* |
| **Zone 2 (Total Inter-zonal ACH) 175 data points:** | | | | | | |
| Forecast: Data Analysis: Ranked by Anderson-Darling | | | | | | |
| Distribution | A-D | A-D **p-Value** | K-S | K-S **p-Value** | Chi-Square | Chi-Square **p-Value** |
| Lognormal | .7349 | **0.028*** | .0622 | **0.056** | 22.36 | **0.013*** |
| Lognormal Parameters **Location = 0.04, Mean = 0.88, Std. Dev. = 0.88** | | | | | | |
| Next best fit: | | | | | | |
| Gamma | 3.1755 | 0.000* | .1177 | 0.000* | 44.92 | 0.000* |
| **Zone 3 (Total Interzonal ACH) 17 data points:** | | | | | | |
| Forecast: Data Analysis: Ranked by: Anderson-Darling | | | | | | |
| Distribution | A-D | A-D **p-Value** | K-S | K-S **p-Value** | Chi-Square | Chi-Square **p-Value** |
| Lognormal | .4851 | **0.079** | .1825 | **0.045*** | 3.4706 | **0.000*** |
| Lognormal Parameters Location = 0.00, Mean = 1.06, Std. Dev. = 1.01 | | | | | | |
| **Next best fit:** | | | | | | |
| Max Extreme | .9352 | 0.017* | .2116 | 0.027* | 3.4706 | 0.062 |
| * Failed fit test | | | | | | |

Additional supplemental spreadsheets are online:

- Housedb.xlsx.
- HouseDB WIN minus CA TX.xlsx.
- Daniel CB HouseDB Win minus CA TX.xlsx.

*Note*: Housedb.xlsx converted from Housedb.dbf