IMPACTS OF MECHANICAL VENTILATION IN WISCONSIN WEATHERIZATION HOMES

FINAL REPORT

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Summary

This report summarizes the final results of post-treatment monitoring of 32 homes treated by the Wisconsin Weatherization Program where mechanical ventilation had been installed based on ASHRAE Standard 62.2 guidelines. For the purposes of the study, special timers were installed to alternately enable and disable the mechanical ventilation in order to gauge the impact of mechanical ventilation on indoor humidity and CO_2 levels, which were tracked at several locations within the home. The homes profiled in this study represent a range of occupancy and tightness levels.

Findings

Some homes in the study showed clear signs of poor indoor air quality without mechanical ventilation—but some did not. Approximately one in five homes in the study had high indoor humidity when the mechanical ventilation was disabled, and more than half had CO_2 levels indicative of inadequate ventilation rates per ASHRAE 62.2 without mechanical ventilation. At the same time, a comparable fraction of homes had low humidity with little CO_2 elevation, even when the installed mechanical ventilation was disabled; these were generally homes with more than 30 cfm of estimated natural ventilation per occupant.

Poor indoor air quality in the absence of mechanical ventilation was generally correlated with the factors used in ASHRAE 62.2 to determine the need for mechanical ventilation. Generally, tight homes and homes with higher occupancy density had higher humidity and CO_2 levels. This suggests the current ASHRAE 62.2 based protocol does help provide useful screening in determining the need for, and amount of, mechanical ventilation based on measured air leakage and occupancy level.

Operation of the mechanical ventilation improved indoor air quality in most homes where it was installed. Indoor humidity and CO_2 levels both showed statistically significant declines in most cases when the mechanical ventilation was enabled. The strongest predictor of the magnitude of the reduction was the amount of mechanical ventilation provided in relation to the estimated natural ventilation rate: homes where the mechanical ventilation rate was high in relation to estimated natural ventilation showed the highest reductions.

The installed mechanical ventilation did not necessarily solve indoor air quality problems. Reductions in indoor humidity were generally on the order of two to three percentage points of relative humidity, which tended to leave high-humidity homes as such. The single exception to this was the one home where an energy recovery ventilator was installed (instead of the exhaust-only ventilation employed at the other sites) with a flow rate well above the ASHRAE 62.2 required level: the ERV's impact on indoor humidity was about twice that of the other sites. This suggests mechanical ventilation rates above ASHRAE 62.2 levels are needed to solve humidity issues in some homes with high moisture loads. This in turn suggests indoor humidity controls should be addressed by other means rather than relying on ASHRAE 62.2 calculated ventilation rates to provide acceptable indoor air quality associated with other pollutants.

Similarly, CO_2 levels remained high in a number of homes, even when mechanical ventilation was enabled. Mean CO_2 levels were often higher in bedrooms than in living rooms, which may be an indication of poor air mixing. This can be more of an issue when there is not a forced air distribution system in the house.

The program protocols led to the installation of mechanical ventilation in some homes that did not appear to need it. The ASHRAE 62.2 protocol led to the installation of mechanical ventilation in some homes that did not exhibit elevated CO_2 or humidity. The program already takes a somewhat conservative approach to installing mechanical ventilation by: a) using only actual occupancy levels; b) adjusting the required mechanical ventilation rate for measured air leakage; and, c) only installing mechanical ventilation if the calculated 62.2 requirement exceeds 15 cfm.

The data from this study suggests further limiting the installation of mechanical ventilation to homes where the estimated natural ventilation rate is less than 30 cfm per occupant would help mitigate the installation of mechanical ventilation where it is not needed and is unlikely to have much impact. Applying such a screen would likely reduce the installation incidence of mechanical ventilation by 5 to 15 percentage points.

Background

Blower-door guided air leakage reduction has been an important component of the Wisconsin Weatherization Program since the mid 1980s. While reducing air leakage saves energy, it also reduces the natural ventilation rate of treated homes, creating concern about indoor air quality following weatherization.

To ameliorate these concerns, the Wisconsin weatherization program initiated a pilot based on ASHRAE Standard 62.2 in 2004.[1] Based on the results of the pilot, the state phased in statewide guidelines for mechanical ventilation based on the standard between July 2005 and January 2006, with some adjustments to the protocol in November 2006.

Under program guidelines, measured air leakage, and the number of occupants and building characteristics are all entered into a computer program that calculates the required amount of mechanical ventilation per ASHRAE 62.2: if the requirement exceeds 15 cfm, mechanical ventilation is installed, typically in the form of a bathroom exhaust fan with a controller for continuous, low-level operation.

In Contract Year 2008 (July 2007 through June 2008) nearly half of all units treated by the program received mechanical ventilation work, which represented slightly more than five percent of all measure spending. Not all of these expenditures were for the installation of new ventilation and not all of the new installations for continuous, low-level operation.

The purpose of this research effort is to explore the impacts of the installed mechanical ventilation on indoor air quality in order to shed light on whether the measure is effective and appropriately targeted.

Approach

To implement the study, a sample of homes was recruited from among those recently treated by five geographically diverse Wisconsin weatherization agencies.[2] The selection criteria for the homes in the study included the homes be single-family, owner-occupied residences, that weatherization work be complete and have included the installation of mechanical ventilation, and (preferably) the homes be heated with a central furnace. We also asked the agencies to identify homes with a range of occupancy levels. The initial recruitment target was six homes per weatherization agency (30 overall), but only 24 homes could be identified and recruited within the initial installation time frame of November, 2008. In addition, some early participants moved out during the study. Additional sites were recruited in February 2009, bringing the total number of homes in the study to 32, with 20 homes involved throughout the entire research time period.

1 American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 62.2-2007, "Ventilation, and Acceptable Indoor Air Quality in Low-Rise Residential Buildings."

2 The weatherization agencies are: ADVOCAP, Inc. (8 homes); North Central CAP, Inc. (2 homes); Project Home Inc. (9 homes); Southwestern Wisconsin CAP (3 homes), West Central Wisconsin CAP (8 homes); and, Social Development Commission of Milwaukee (2 homes).

After recruitment by the weatherization agency, a member of the study team visited each home to install monitoring equipment and a special study timer to periodically disable the mechanical ventilation (discussed below), and to gather details about the home and the household. The installations occurred throughout the month of November 2008, with additional installations for new recruits in early February 2009.

The monitoring points and equipment are detailed in Table 1. The key items of interest were humidity and CO_2 levels in the various monitored locations, but the monitoring included tracking the on/off status of the study timer, the ventilation equipment, and the furnace air handler. We also installed a temperature sensor above the kitchen range for homes with gas ranges as an aid to distinguishing cooking-related CO_2 from occupant generated CO_2.

The core concept of the study approach was to gauge the impact of mechanical ventilation by repeatedly disabling and enabling the installed ventilation in a sample of homes where it had been installed, and observing changes in CO_2 and humidity levels. All but one of the homes employed exhaust-only ventilation (typically in a bathroom), and most used fan controllers as a means to adjust the fan flow by reducing voltage to the fan and/or cycling the fan on/off for a fixed number of minutes per hour. To implement the on/off study design for this equipment, a special timer was wired into the circuit such that power was maintained to the existing fan controller at all times, but power to the fan itself was periodically disabled. The study timer was configured to enable mechanical ventilation for approximately 100 hours, then disable it for a similar length of time in a repeating pattern throughout the monitoring period. The on/off time periods were increased to 300 hours at the onset of Round 2 in February.

In addition, a separate programmable timer was installed on the furnace air handler to operate the air handler continuously for a few hours each week as an aid to assessing the normal degree of indoor air mixing. This was done only if the occupants were amenable (25 agreed), and the timers were programmed to operate at times that would not be bothersome to the household.

Table 1

Monitoring Locations, Parameters, and Sampling Rates

Monitoring Location and Parameters	Equipment	Sampling Rate
Main living space: CO_2, temperature and humidity	Telaire 7001 (CO_2) connected to Hobo U12 (temperature and humidity	10 minutes
Master Bedroom: CO_2, temperature and humidity	Telaire 7001 (CO_2) connected to Hobo U12 (temperature and humidity)	10 minutes
Bathroom where the ventilation equipment was located (or in a main bathroom, if the ventilation equipment was not in a bathroom): temperature and humidity	Hobo U12	10 minutes
Main thermostat: temperature and humidity	Hobo H8	30 minutes
Above kitchen range (in homes with gas ranges): temperature	Hobo Pro	2 minutes
Furnace air handler operation	Hawkeye current switch connected to Hobo U11 State logger	Time stamped on/off events
Installed mechanical ventilation operation	Hawkeye current switch connected to Hobo H8 state logger	Time stamped on/off events
Mechanical ventilation status controller	Relay connected to Hobo H8 state logger	Time stamped on/off events

The CO_2 sensors were calibrated against known calibration gas prior to deployment in the field. The loggers recorded data during two periods (November to February and February to June), with an intermediate download of data conducted in between periods.

In addition to on-site data gathered about the home, we also relied on information from the weatherization agency that included; area and volume of the home, post-treatment air leakage, the number of occupants, estimated natural ventilation rate, and the calculated ASHRAE 62.2 mechanical ventilation requirement at the time the mechanical ventilation rate was determined.

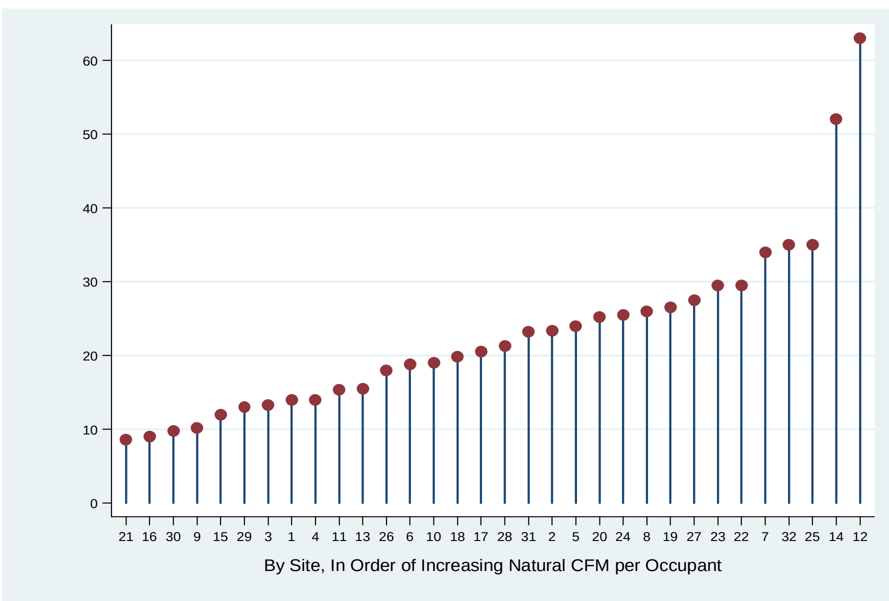
Characteristics of the Homes in the Study

The 32 homes monitored in the study ranged in occupancy and air tightness (See Appendix A, Tables A-1 and A-2 for more detailed data). Of particular interest, is the number of occupants in relation to the size and tightness of the home: small, tight homes with more occupants could be expected to have more issues with indoor air quality than large, loose homes with fewer occupants.

We used estimated natural infiltration per occupant as a single indicator variable that combines the three dimensions of occupancy level, home size, and air tightness. Our estimates of natural ventilation rates come from calculations procedures in ASHRAE Standards 119 and 136, as implemented in the Ziptest Pro^2™ software from R.J. Karg Associates used by the program.[3,4] These calculations make use of blower-door measured air leakage, home size (and height) and a climate factor to estimate average natural ventilation rates based on. As such, they are estimates of seasonal average natural ventilation derived from air leakage testing—rather than measured natural air change rates, which in any event vary considerable with changes in the day-to-day weather.

Natural cfm per occupant ranged from less than 10 cfm (Sites 21 and 16) to more than 60 cfm (Site 12), as Figure 1 shows. The two highest values were for homes with single occupants.

Figure 1
Estimated Natural Ventilation per Occupant



[3] ASHRAE Standard 119, "Air Leakage Performance for Detached Single-Family Residential Buildings", American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1988.

[4] ASHRAE Standard 136, "A Method of Determining Air Change Rates in Detached Dwellings", American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1993.

Required and Supplied Mechanical Ventilation

As noted previously, the installation of mechanical ventilation in the Wisconsin program is driven by ASHRAE Standard 62.2, which stipulates that homes be ventilated at a rate that depends on both the number of occupants and the size of the home:

- *ASHRAE 62.2 target ventilation rate = 7.5 cfm per occupant +0.03 cfm per square foot of living space*

The standard has a default credit for natural ventilation of 0.02 cfm per square foot of living space, the required mechanical ventilation is:

- *Required mechanical ventilation rate = 7.5 cfm per occupant +0.01 cfm per square foot of living space*

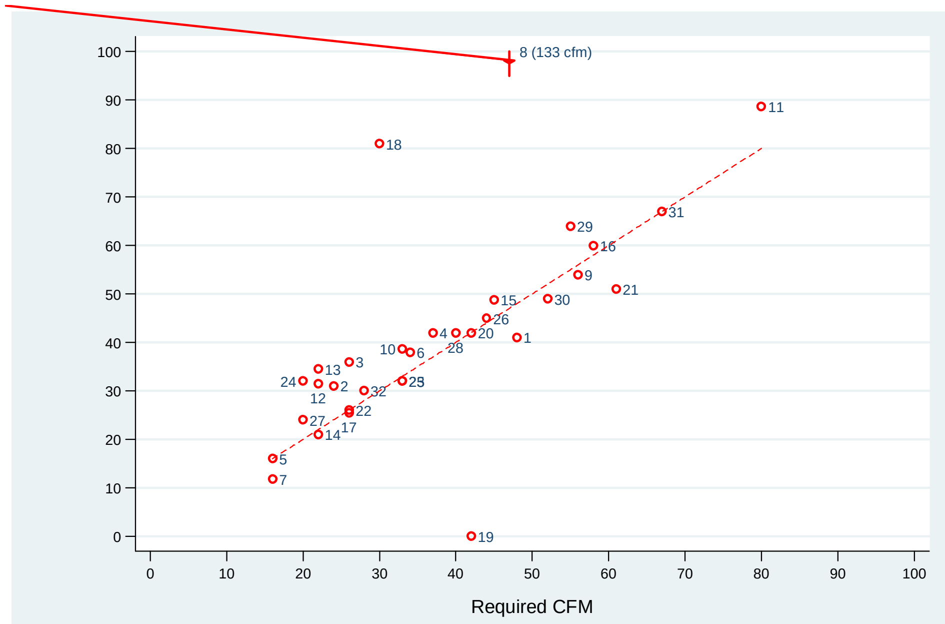
There are, however, two important nuances regarding the latter formula. First, ASHRAE 62.2 allows for reducing the required amount of mechanical ventilation in existing homes if the estimated natural ventilation exceeds the default credit in the standard of 0.02 cfm per square foot of floor area. The Wisconsin program uses this credit provision to reduce the required amount of mechanical ventilation based on the estimated natural ventilation rate, and program guidelines require the installation of mechanical ventilation only if the adjusted requirement exceeds 15 cfm.

Second, as the standard is currently written, the occupancy-based portion of the required ventilation rate is expressed in the standard in terms of number of bedrooms, with an assumption that occupants = bedrooms +1. The standard does provide for using a higher number “where higher occupancy densities are known,” and provides for using a lower figure “when approved by the authority having jurisdiction.” The Wisconsin program simply bases the mechanical ventilation calculation on the number of occupants in the home at the time of treatment, and does not use the bedrooms proxy. The Wisconsin program also includes the basement for calculating the floor area for most homes.

Figure 2 (and Appendix A) documents the required and supplied amount of mechanical ventilation for each site. One issue that arose is the number of occupants had changed for some sites between the time the original ventilation calculations were made and when the monitoring was installed.

Figure 2

Supplied vs. Required (as per ASHRAE 62.2) and Level of Occupancy at the Time the Monitoring Equipment was Installed



*Based on occupancy at the time monitoring equipment was installed.
Dashed red line represents a slope of unity.

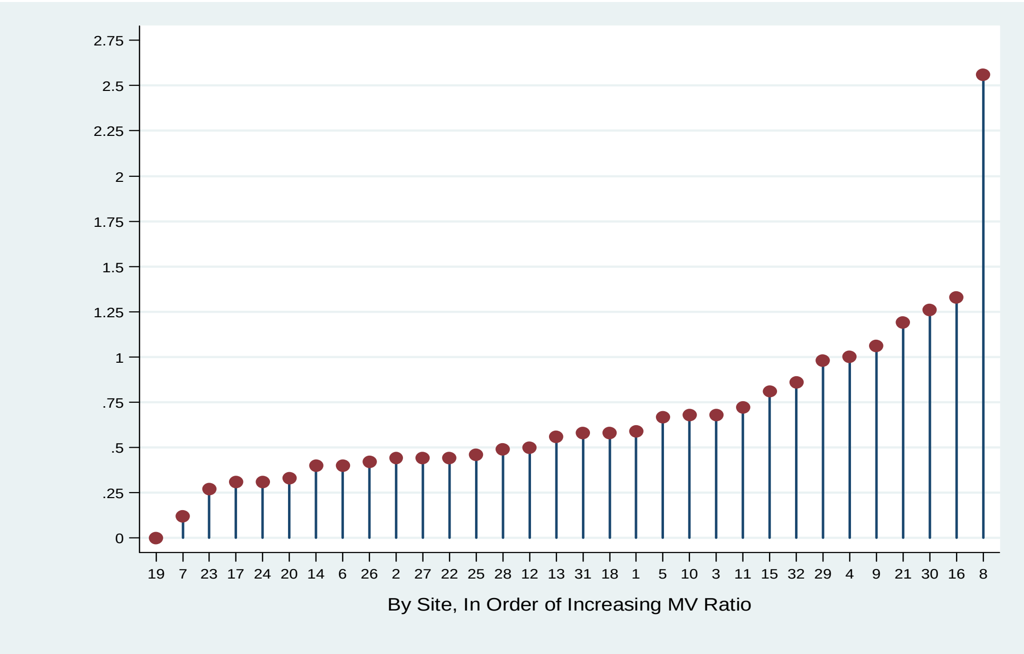
The required amount of mechanical ventilation from ASHRAE 62.2 varied from 9 to 80 cfm (based on the most recent occupancy), and except for Site 18, the supplied amount of ventilation matched this requirement reasonably well. At Site 18, there appears to have been a mix-up about whether the fan in question cycled or ran continuously, which led to an actual ventilation rate approximately 50 cfm more than required by ASHRAE 62.2.

With one notable exception, the installed mechanical ventilation was in the form of exhaust-only fans, generally located in a bathroom (though the fan was installed in the kitchen at Sites 7 and 27 and in a hallway at Site 9). The fans either ran continuously or cycled a fixed number of minutes per hour, and most were wired to wall-switch controllers with short-term, occupant-controlled boost capability.

In contrast to the other sites, the mechanical ventilation installed at Site 8 was an energy recovery ventilator (ERV) that ran continuously at about 133 cfm, well above the ASHRAE 62.2 required rate of 47 cfm. Unfortunately, unforeseen wiring issues during the initial monitoring installation meant the system was not periodically disabled in Round 1. Corrections to the wiring were made between the first and second monitoring period, so the system was periodically disabled in Round 2.

We also expressed the supplied mechanical ventilation as a fraction of the estimated natural ventilation (Figure 3). Homes with a low value of this ratio might be expected to see only a

Figure 3
Ratio of Supplied Mechanical Ventilation to Estimated Natural Ventilation



small impact on indoor air quality from mechanical ventilation, while homes with a high value would be more likely to experience a larger impact.[5] As we will show later, humidity and CO_2 changes associated with mechanical ventilation were in fact well correlated with this ratio.

The sites on each end of Figure 3 are noteworthy. First, the ERV installed at Site 8 provided a large amount of mechanical ventilation (133 cfm), relative to the estimated natural ventilation (52 cfm, based on a final blower door leakage value of 870 CFM_{50}). Second, Site 19 is shown as having no mechanical ventilation: in fact, the mechanical ventilation controller for this site broke during installation of the monitoring equipment, so there was no mechanical ventilation during the monitoring period (the site was dropped in February). Rather than eliminate the data from this site, we created pseudo-operation periods for mechanical to serve as a control check on whether our methods yield no effect when in fact there is no mechanical ventilation at all.

[5] Note that one should not assume that total ventilation is simply the sum of mechanical and natural ventilation. While the question of superposition of mechanical and natural ventilation can be complex, a general rule of thumb for the exhaust-only ventilation in this study is that only ½ of the mechanical ventilation is incremental: in other words, if natural ventilation of 50 cfm is occurring in a home, and one turns on a 50 cfm exhaust fan, overall ventilation will increase by 25 cfm to 75 cfm. For balanced ventilation systems, such as the ERV at Site 8, all mechanical ventilation is incremental to natural ventilation. See Palmiter, L., and T. Bond. 1991. "Interaction of Mechanical Systems and Natural Infiltration." Proceedings of the AIVC 1991 Conference on Air Movement and Ventilation Control Within Buildings, 1:285-295. Coventy, Great Britain: The Air Infiltration and Ventilation Centre.

Results

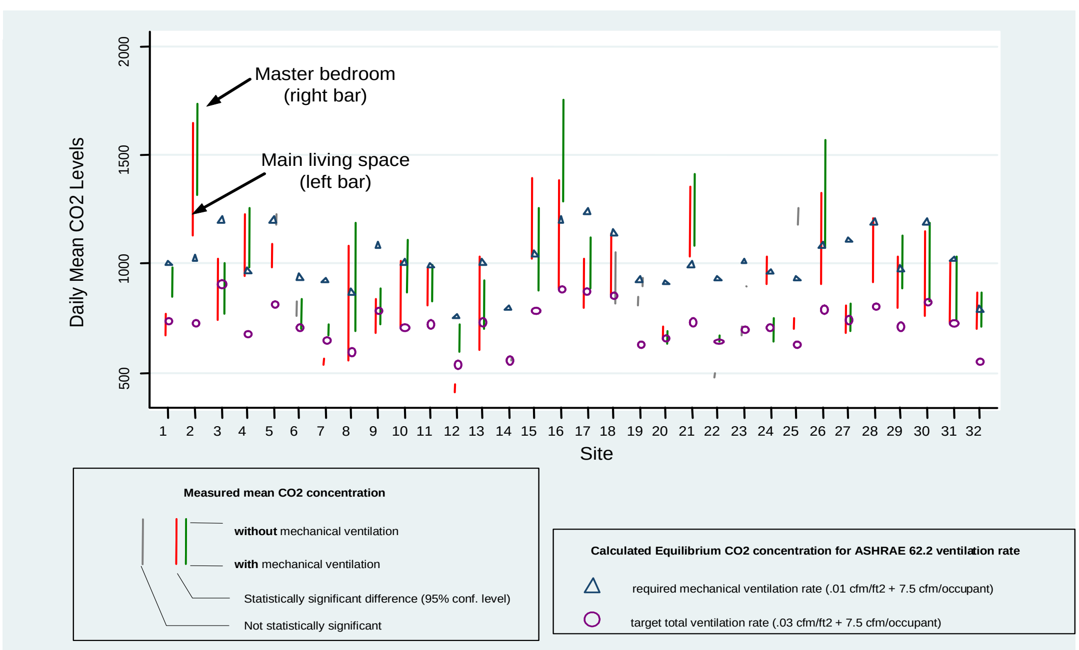
Carbon Dioxide Levels

Measured CO_2 levels, used as an indication of in-home ventilation rates, allow us to answer two fundamental questions regarding the effectiveness of installing mechanical ventilation systems. First, does the use of mechanical ventilation within a home result in statistically significant reductions in indoor CO_2 levels (an indication of higher ventilation rates)? Second, do such reductions indicate adequate ventilation per ASHRAE 62.2?

We find the answer to the first question to be rather succinct. The green and red vertical bars in Figure 4 represent statistically significant reductions in mean CO_2 levels within the main living spaces and bedrooms of the 32 study sites. The ends of each bar represent mean CO_2 levels with (bottom) and without (top) mechanical ventilation. Although the magnitudes in changes vary substantially across sites, mechanical ventilation resulted in a statistically significant reduction of mean CO_2 levels in a great majority of the study homes. Note there is substantial variation in mean CO_2 levels, both across sites and across rooms within sites. The answer to the second question is more complex and requires an understanding of occupancy driven CO_2 generation rates and equilibrium theory.

Figure 4

Comparison of Mean CO_2 Levels for Main Living Space and Bedrooms, with and without Mechanical Ventilation



Although indoor CO_2 is a highly dynamic quantity—varying minute-by-minute based on occupancy, activity level, and air exchange rate in individual rooms—it can provide a useful rough indicator of whether a home is ventilated at the target ventilation rate stipulated by ASHRAE 62.2 (7.5 cfm per occupant +0.03 cfm per square foot). Making this assessment requires estimating the indoor CO_2 level we would expect if the home was ventilated at the 62.2 target rate. CO_2 levels that frequently exceed what we would expect if the home were ventilated at the 62.2 rate are good evidence actual ventilation falls short of the 62.2 target (assuming our calculations are based on the correct number of typical occupants).

Conversely, while low CO_2 levels *may* indicate high ventilation rates, they may also signify people are not typically home long enough for CO_2 to build up to levels that would reveal inadequate ventilation. Thus, indoor CO_2 tends to be a one-side test of ventilation rates: high CO_2 levels reveal poor ventilation, but low CO_2 levels do not necessarily demonstrate adequate ventilation.

We rely on equilibrium theory to calculate the maximum level of CO_2 we would typically expect if a home receives the ASHRAE 62.2 *target* ventilation rate.[6] Under steady-state conditions (i.e., constant air exchange rate and constant CO_2 generation rate by occupants, with good mixing of indoor air), this theory states the indoor CO_2 concentration will rise until the amount CO_2 removed each minute through ventilation is equal to the amount generated by the occupants.[7] For ease of use, we refer to the equilibrium CO_2 concentration corresponding to the ASHRAE 62.2 target of .03 cfm/sq ft as $TGT_{eq.}$

Similarly, we can also calculate the equilibrium CO_2 concentration we would expect if the home receives only the ASHRAE 62.2 required *mechanical* ventilation (as will sometimes occur when there is no natural stack-effect or wind-driven ventilation). The 62.2 required mechanical ventilation rate is lower than the overall target ventilation rate, and so the calculated equilibrium CO_2 concentration is higher. For ease of use, we refer to equilibrium CO_2 concentration corresponding to the mechanical component of the ASHRAE 62.2 target ventilation rate as MV_{eq}.

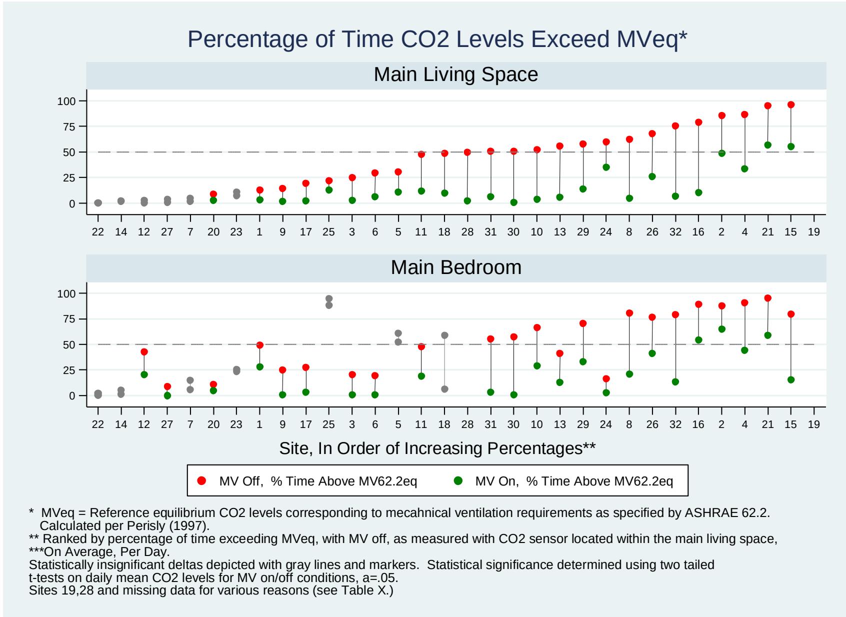
These calculated equilibrium levels are shown in Figure 5 in relation to the observed mean CO_2 concentrations. In most cases, mean CO_2 levels exceed TGT_{eq} at least some fraction of time, whether or not mechanical ventilation is enabled. In most cases, the use of mechanical ventilation resulted in mean CO_2 levels falling below MV_{eq}.

6 See Persily, Andrew, "Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide." ASHRAE Transactions, Vol. 103, No. 2, 1997. to establish equilibrium CO2 levels associated with these ventilation rates using assume CO2 generation rates (which we age-adjusted for households with children).

7 Assumptions about the CO_2 generation rate per person are important for this calculation. We used 0.011 cfm/occupant for adults, but 30% of this value for children ages 0-5, and 70% for children ages 6-17.

Figure 5

Percentage of Time CO_2 Levels Exceeded MV_{eq}



However, comparing *average* CO_2 levels to the calculated 62.2 equilibrium levels does not provide a good sense of how frequently actual CO_2 levels exceed these thresholds. Accordingly, Figure 6 shows the fraction of the time (per each 24-hour period, averaged across days) measured levels exceeded the mechanical ventilation threshold. Note these percentages only indicate "how often" and not "by how much" these levels were exceeded. In most cases, enabling the mechanical ventilation resulted in CO_2 levels falling below MV_{eq} more than 75 percent of the time in the main living space. However, the sites most frequently exceeded MV_{eq} (Sites 4, 16, 21 and 28) continued to do so, even when mechanical ventilation was enabled.

Because it corresponds to a lower ventilation rate, MV_{eq} can be considered to be a less stringent threshold than TGT_{eq}. Figure 7 shows the percentage of time that hourly CO_2 levels exceeded TGT_{eq}. Few homes exhibited CO_2 levels indicating that the ASHRAE 62.2 target ventilation rates were frequently met.

Figure 6

Percentage of Time Hourly CO_2 Levels Exceeded MV_{eq} on a Daily Basis

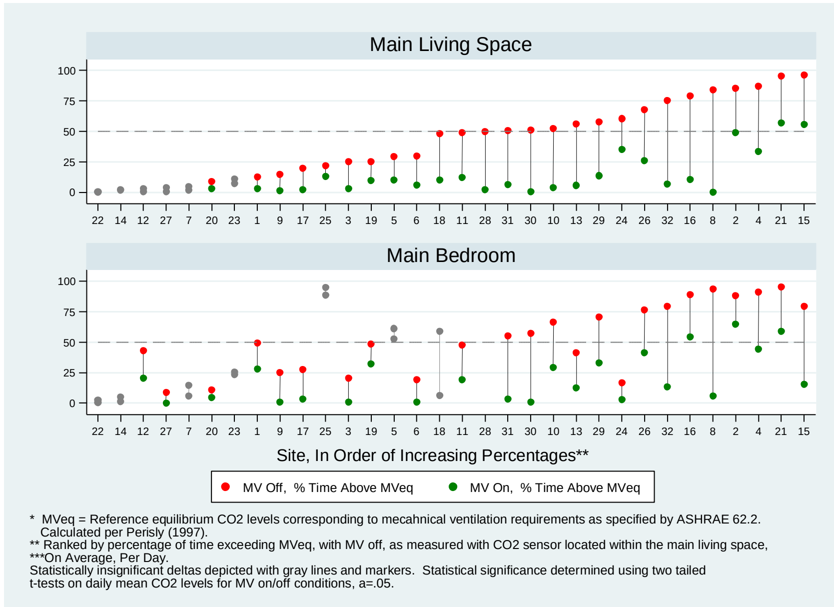
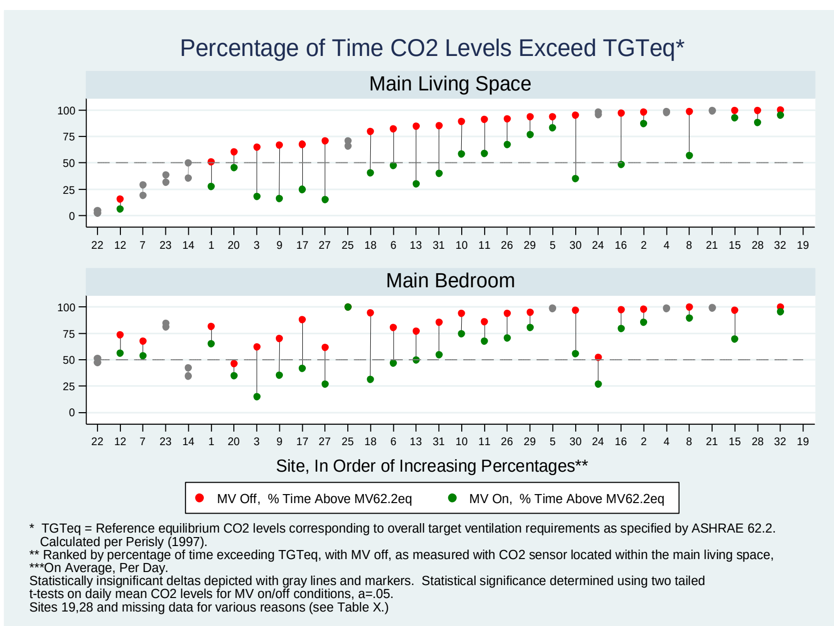


Figure 7

Percentage of Time CO_2 Levels Exceeded TGT_{eq}



Using the relationships depicted above, we classified the homes into three categories according to whether their CO_2 levels: a) did not *frequently*[8] exceed the MV_{eq} threshold, even when the mechanical ventilation was disabled, b) *frequently* exceeded this threshold when the mechanical ventilation was disabled, but not when it was enabled; or, c) *frequently* exceeded the threshold whether the ventilation was enabled or disabled (Table 2).

Table 2
Classification of Sites by Whether CO_2 Frequently Exceeded MV_{eq}

Space	**Measured CO_2 Freq. less than MV_{eq}, even with mechanical ventilation disabled**	**Measured CO_2 Freq. greater than MV_{eq}, but only with mechanical ventilation disabled**	**Measured CO_2 Freq. greater than MV_{eq}, even with mechanical ventilation enabled**
Main living area	1, **3**, **7**, **9**, 12, **14**, 17, **20**, **22**, 23, 25, and **27**	5, 6, **8**, 10, **11**, **13**, 16, **18**, 28, 29, **30**, **31**, and **32**	**2**, **4**, **15, 21,** 24, and **26**
Master bedroom	**3**, 6, **7, 9**, **14**, **20**, **22**, 24, and **27**	**8**, **11**, 12, **13**, 15, 17, **18**, 23, **30**, **31**,and **32**	1, **2, 4,** 5, 10, **15,** 16, **21**, 25, **26**, and 29
Bolded sites show consistency in belonging to the same category across rooms. * Site 28 missing BD CO_2.			

By this measure, roughly a third of the sites fell into the first category, indicating they either had minimally adequate ventilation without the added mechanical ventilation, or were not typically occupied enough hours of the day for CO_2 to build up to higher levels to indicate inadequate ventilation. The remainder of homes showed elevated CO_2 levels suggesting total ventilation was below even the 62.2 required mechanical ventilation rate when the ventilation was disabled. In many cases (especially within the main bedroom; this only occurred in the living space of six study homes), CO_2 levels remained above what we would expect if the home was receiving the 62.2 required ventilation rate. Most of the homes in this group were either homes with high occupancy (Sites 15, 21, and 26), were homes which were measured to be relatively air-tight (Sites 4 and 21) or did not use forced air furnaces as a primary heating source (Site 2). The site identifiers categorized by Table 2 are **bolded** if the bedroom and living space fall within the same category. The fact that many sites remain un-bolded is an indication that inadequate mixing may preclude detecting equal mechanical ventilation impacts across rooms at the same site.

There appear to be more bedrooms falling into the third category, which may indicate these rooms are sufficiently segregated from the remainder of the home such that significant CO_2 buildup occurs on a more frequent basis. This is not surprising; bedrooms are often located within a home's extremities, and occupants may further segregate the bedroom by closing bedroom doors during sleeping hours or when not at home. As such, the main living space, in part, because they are generally larger, centrally located and open to several adjoining rooms may offer a more accurate portrayal of whole-home CO_2 levels.

[8] We consider 'less than 25 percent of the time' to be 'infrequent.'

Predictors for Effective Mechanical Ventilation

Up to this point, our results have focused on demonstrating whether or not mechanical ventilation had a discernible effect in reducing indoor CO_2 levels and whether these levels approach those expected under compliance with ASHRAE 62.2. We examined three contributing factors that seemed to explain whether mechanical ventilation provided a substantial incremental gain in overall home ventilation rates. These factors were estimated natural ventilation per occupant, the ratio of mechanical to natural ventilation (MV ratio) and CO_2 levels in the absence of mechanical ventilation.

Natural Ventilation Per Occupant. Estimated natural ventilation per occupant can be relatively high if a home is either quite leaky, or if a home is moderately airtight but has a low occupancy rate. Figure 8 shows a plot of average daily mean CO_2 levels versus occupancy adjusted natural ventilation rates. The plot shows a relatively strong correlation between estimated natural ventilation rates and elevated mean CO_2 levels. Homes with less natural ventilation per occupant generally exhibit elevated levels of CO_2. We also examined the degree to which levels of CO_2 vary across seasons and varying degrees of natural ventilation (not shown). We found mechanical ventilation has the smallest impact in leakier homes during the winter heating season, most likely due to the greater role "stack-effect" driven ventilation plays when the difference between indoor and outdoor temperatures are greatest.

MV Ratio. We found the ratio of mechanical to natural ventilation (MV ratio) is a relatively reliable predictor of whether the supplied level of mechanical ventilation will lead to statistically significant reductions in mean CO_2 levels. Figure 9 shows homes not exhibiting a statistically significant reduction in daily mean CO_2 levels have supplied mechanical ventilation per occupant less than or equal to half of the estimated natural ventilation per occupant (MV Ratio = 0.5).

CO_2 Levels in the Absence of Mechanical Ventilation. Finally, we find homes exhibiting the highest levels of CO_2 also consistently exhibit the greatest response to mechanical ventilation. Figure 10 succinctly shows the correlation (for the sensor located in the main living space) between MV induced reductions in CO_2 and CO_2 levels in the absence of mechanical ventilation. Mechanical ventilation has a smaller (or statistically insignificant) effect in homes where CO_2 levels in the absence of mechanical ventilation are low to begin with, which is what was expected to happen.

Figure 8

CO_2 Levels in the Absence of Mechanical Ventilation vs. Ventilation per Occupant

Figure 9

Percentage Change in CO_2 levels vs. CO_2 Levels in the Absence of Mechanical Ventilation

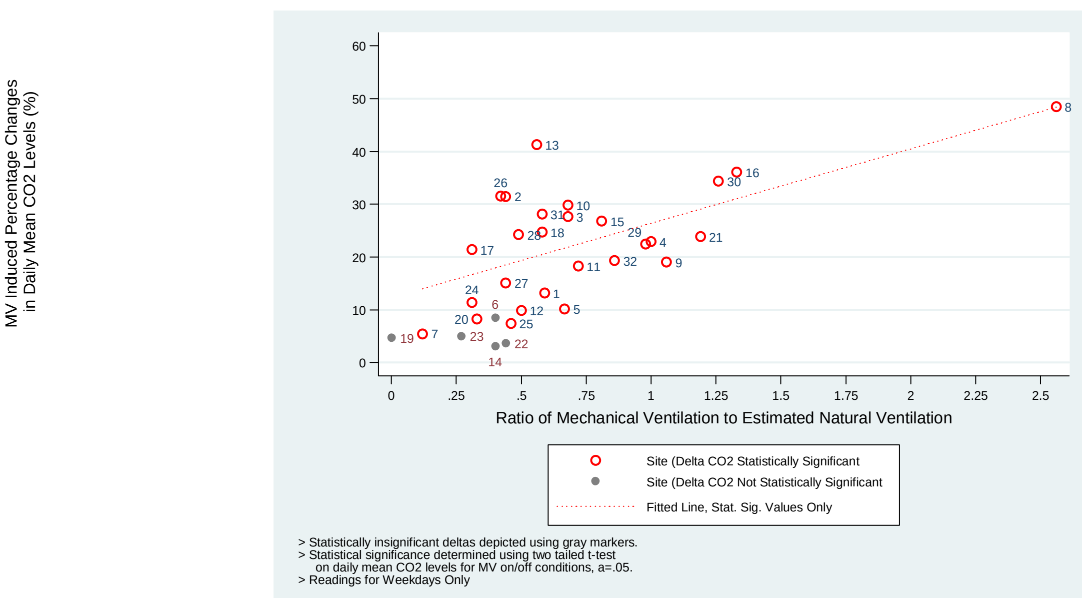
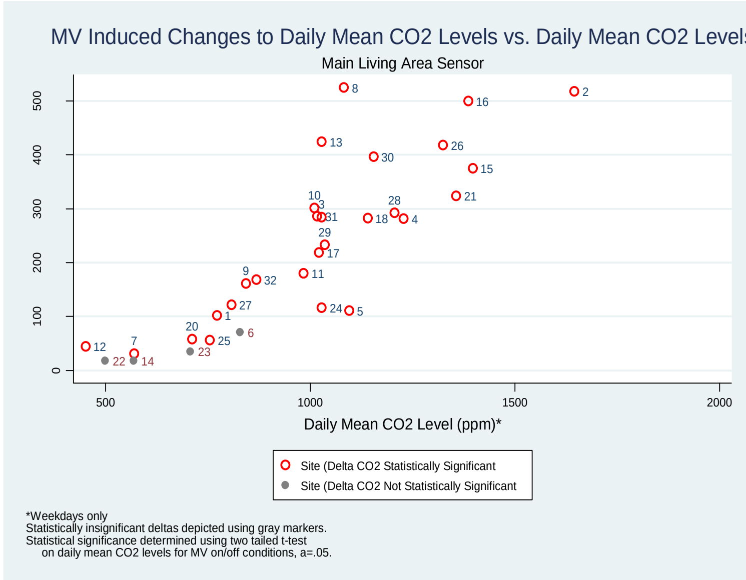


Figure 10

MV Induced Reductions in Daily Mean CO_2 Levels vs. Mean CO_2 Levels

In the Absence of Mechanical Ventilation, Main Living Space



In sum, mechanical ventilation appears to substantially reduce indoor CO_2 levels when one or more of the following conditions are met:

1) Estimated natural ventilation per occupant is low.
2) The ratio of supplied mechanical ventilation to the estimated natural ventilation is greater than 0.50.
3) CO_2 levels in the absence of mechanical ventilation are high to begin with.

Humidity

Indoor humidity can be viewed as a balance of competing forces: human respiration, bathing and other sources of indoor moisture add humidity to the indoor environment, while infiltration and mechanical ventilation remove humidity by replacing moist indoor air with drier outdoor air.[9] The rate at which infiltration and ventilation remove humidity depends on the rate of air exchange as well as the humidity of the outdoor air. Infiltration is higher in colder weather, and the amount of moisture in cold air in the winter is generally quite low; these two factors combine to create high drying potential in the winter. In the spring and fall when outdoor temperatures

[9] At least this is nearly always true during the heating season; in the summer, infiltration and ventilation can just as easily add humidity to the home.

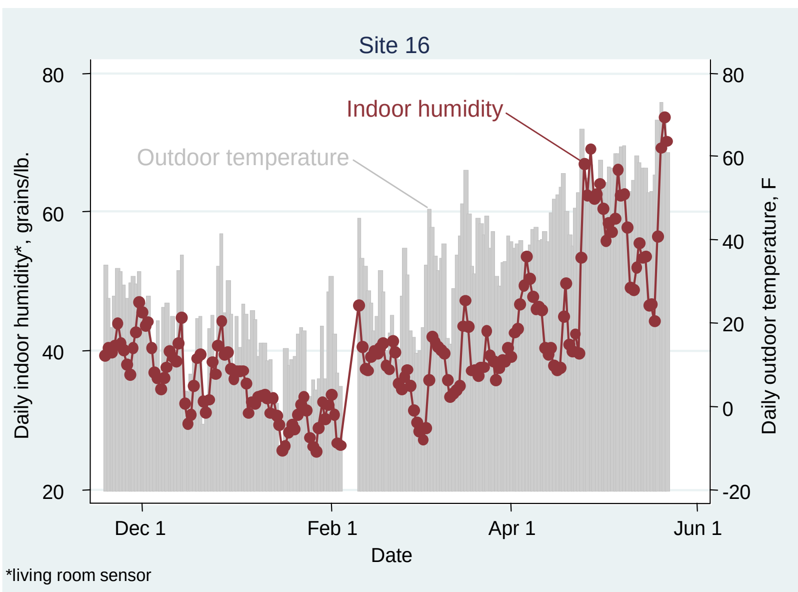
are warmer, there is less stack-effect driven infiltration, and the humidity of outdoor air is higher (and more variable) resulting in less drying potential. Finally, indoor furnishings and building materials tend to absorb and release moisture over time, and thus act to buffer sharp changes in humidity.

All of this adds up to a highly dynamic day-to-day situation for analyzing indoor humidity and how it is affected by adding mechanical ventilation. Most homes show a strong correlation between indoor humidity and outdoor temperature due to the strong effect the latter has on both air exchange rate and dryness of the infiltrating air. Figure 11 shows how indoor humidity tends to rise and fall with outdoor temperature for a typical site in the study.[10]

We used regression analysis to estimate the impact of mechanical ventilation on indoor humidity for each site and sensor location. The regression analysis took into account outdoor temperature and humidity, as well as the operating status of the mechanical ventilation. We also accounted for lags in how indoor humidity responds, and in some cases we controlled for prolonged periods when a home was unoccupied based on our examination of the CO_2 data.

Figure 11

Typical Indoor Humidity Trend with Outdoor Temperature



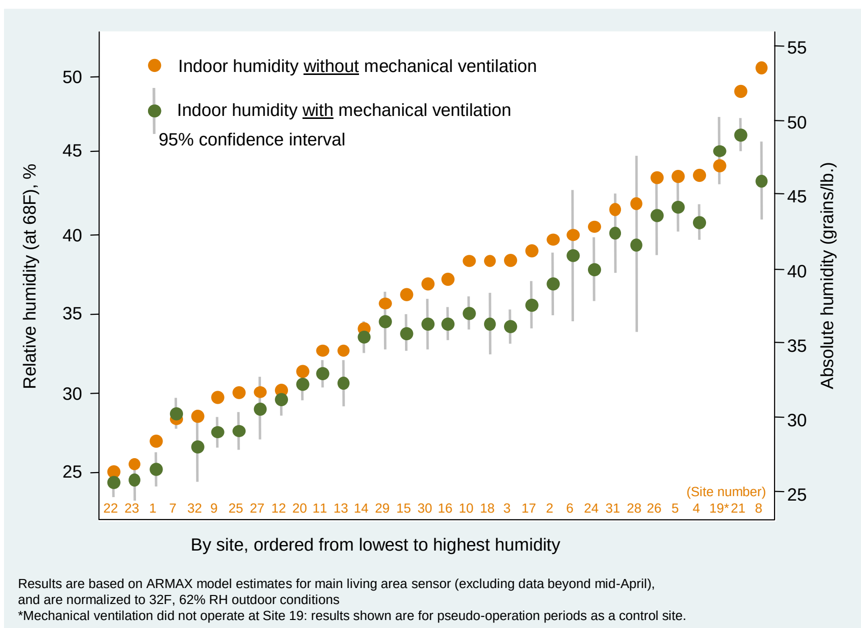
[10] Note that our analysis of humidity here focuses on *absolute* humidity, which we express in grains of water vapor per pound of dry air (grains are a unit of mass measurement: there are 7,000 grains in a pound).

This approach allowed us to control for the confounding effects of weather and occupancy on indoor humidity, as well as to express the results on a weather-normalized basis.[11] The results (for the main living area sensor) show a substantial range of indoor humidity without mechanical ventilation across the sites, and nearly all sites showed a decline in indoor humidity when the mechanical ventilation was operated (Figure 11). However, the drop is statistically significant at approximately half of the sites, and is dramatic only at Site 8. In particular, with the exception of Site 8, homes on the high end of indoor humidity remained as such even after the exhaust-only mechanical ventilation was enabled.

The results Figure 12 are for the main living room sensor. The regression estimates for the master bedroom sensor generally tracked the main living area sensor closely (Figure 13), but the bathroom sensor, where the exhaust-only mechanical ventilation was usually installed, showed somewhat sharper declines in approximately half the cases (though statistically significantly so at only one site).

Figure 12

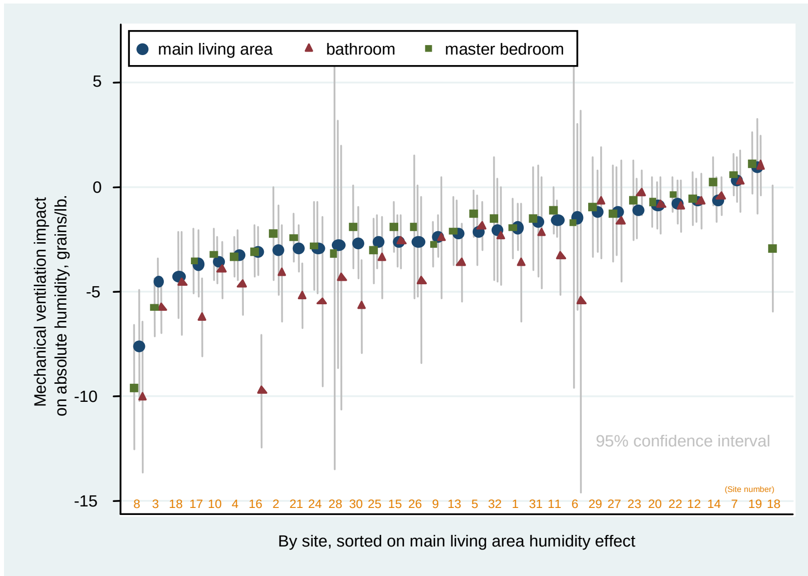
Normalized Heating Season Indoor Humidity with and without Mechanical Ventilation



11 The details of this analysis can be found in Appendix E.

Figure 13

Mechanical Ventilation Impact on Absolute Humidity, by Sensor Location



One might argue our experimental protocol itself limits the observed impact of mechanical ventilation on indoor humidity. If it takes a substantial amount of time for the effects of the ventilation to be felt, then alternately operating and disabling the ventilation every 100 or 300 hours, might preclude ever seeing the full impact. With this concern in mind, we undertook a more detailed look at trends in humidity as a function of the elapsed time within each operating cycle. This analysis (which is explained in Appendix E) suggests the results above may somewhat underestimate the full impact of the mechanical ventilation, though not likely by a large amount.

We looked for factors that would help explain both differences in humidity levels across homes, as well as variation in the impact of mechanical ventilation on indoor humidity. In terms of humidity levels in the absence of mechanical ventilation, the homes in the study ranged from overly dry to overly humid. When the regression results are used to estimate indoor humidity on a cold winter day (0° F outdoor temperature), nine sites are estimated to have indoor relative humidity below 25 percent (at an indoor temperature of 68° F), and six homes would have indoor relative humidity above 35 percent. The strongest predictor of indoor humidity in the absence of mechanical ventilation is the estimated natural ventilation rate per occupant, but even here the correspondence is relatively weak (Figure 14).

There is a stronger correlation between the *change* in indoor humidity due to the installed mechanical ventilation and the ratio of mechanical to (estimated seasonal) natural ventilation cfm, as shown in Figure 15. Generally, sites where the mechanical ventilation was a small fraction of the estimated natural ventilation rate, showed small changes in indoor humidity, while sites where this ratio was high showed larger reductions in humidity.

Figure 14
Indoor Humidity without Mechanical Ventilation, vs. Natural Ventilation per Occupant

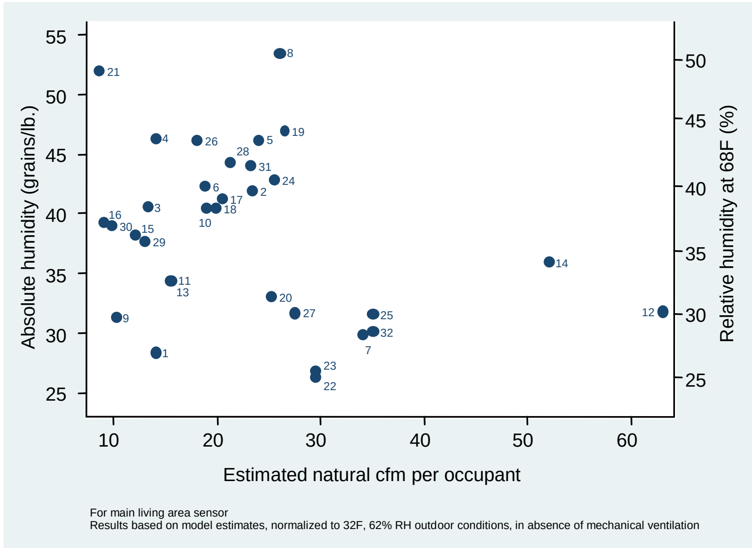
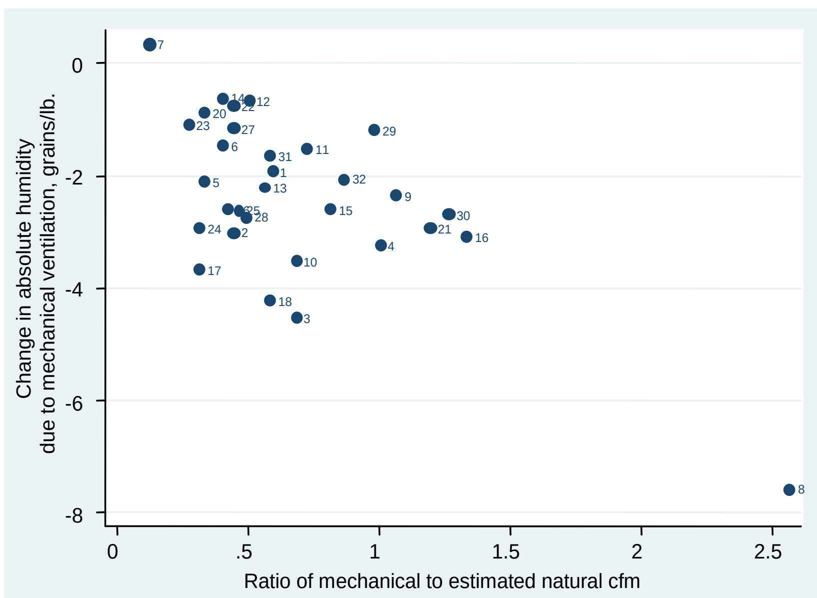


Figure 15
Mechanical Ventilation Impact on Indoor humidity, vs. Ratio of Mechanical to Natural Ventilation

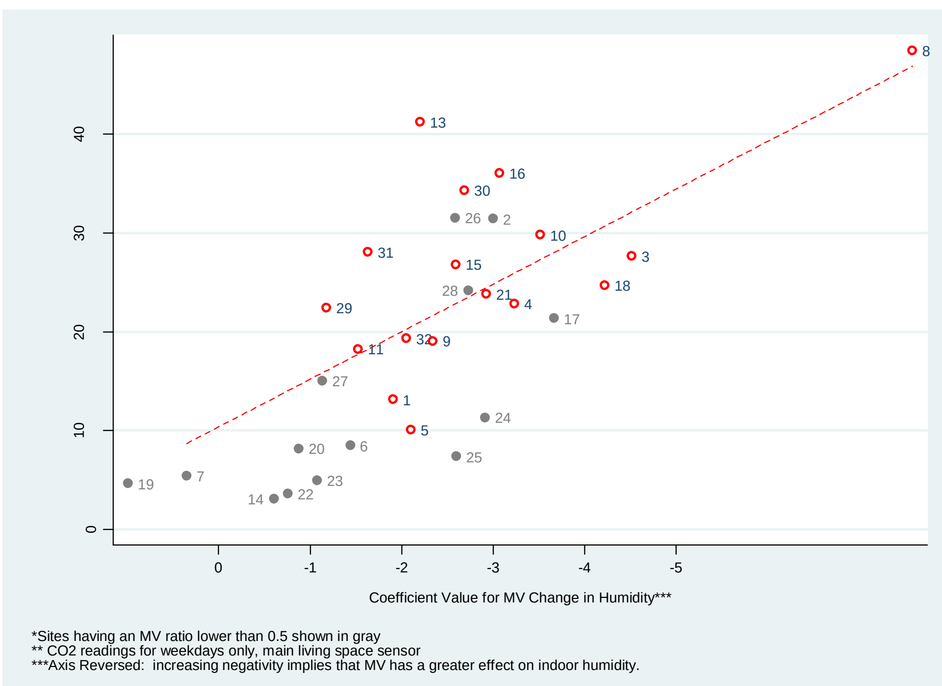


Site 8 stands apart as having a very high ratio of mechanical to natural ventilation. This site was the only one where an energy recovery ventilator (ERV) was installed (instead of the exhaust-only ventilation employed at the other sites). The large amount of mechanical ventilation provided by the ERV resulted in a commensurately large impact on indoor humidity.

Correlation Between Humdity and CO_2 Effects

The results we have presented in the previous two sections show mechanical ventilation resulted in non-negligible changes in mean CO_2 and absolute humidity levels at a number of the study sites. These changes are tied to several parameters, most notably the ratio of supplied mechanical ventilation to estimated natural ventilation per occupant (or MV ratio). We now examine whether these effects are concurrent across sites. Figure 16 shows both humidity and CO_2 effects are correlated with the MV ratio. The majority of homes (10 of 14) with an MV ratio of less than 0.5 (depicted using gray markers) are concentrated in the lower left hand corner of Figure 16**.** These sites show the smallest reductions in both CO_2 and indoor humidity.[12] Although they have smaller MV ratios, Sites 17 and 26 rank tenth and seventh in occupation density (occ/cu ft), site 28 ranks within the top five in age-adjusted occupancy and Site 2 is somewhat abnormal in that it is the only site that uses a hydronic system for its primary heating source.

Figure 16
Correlation between the Percent Reductions in Daily Mean CO_2 Levels and the Regression Coefficient Explaining the Impact of Mechanical Ventilation in Reducing Indoor Humidity



[12] β_3 is the estimated coefficient for the component of the ARMAX regression function that explains indoor absolute humidity as a function of the percent of time during the day that mechanical ventilation was operating (See Appendix E).

Discussion

The data suggest mechanical ventilation is needed in many (but not all) of the study homes where it was installed. Approximately one in five homes in the study had high humidity, and most of the study homes had CO_2 levels suggestive of ventilation rates less than those stipulated by ASHRAE 62.2. It does not seem the program is unnecessarily installing mechanical ventilation in a large percentage of homes that do not need it. Because this study looks only at homes that received mechanical ventilation, we cannot reach conclusions about the extent to which the protocol fails to install mechanical ventilation in homes that need it.

Mechanical ventilation had a clear impact on both humidity and CO_2, with the larger impacts in homes where the mechanical ventilation rate was high in relation to natural ventilation, and smaller impacts where the mechanical ventilation was small in relation to the estimated average natural ventilation rate.

Results of the monitoring showed the installation of mechanical ventilation did not necessarily eliminate indoor air quality issues, and in some cases was installed in homes that did not appear to need it.

Enabling the mechanical ventilation did not significantly ameliorate humidity issues in homes showing elevated humidity without mechanical ventilation and frequently left CO_2 levels above those if the homes were ventilated at ASHRAE 62.2 rates. For humidity, most sites showed only a two to three percentage point reduction in relative humidity associated with mechanical ventilation, an effect inadequate to ameliorate humidity issues in homes on the high end of the humidity scale. The one site showing a substantial reduction in humidity (Site 8) is notable both in that the installed mechanical ventilation provided nearly three times the 62.2-required ventilation, as well as being the sole site where balanced ventilation (an ERV) was installed instead of exhaust-only ventilation. Both of these factors help explain the greater impact seen at this site.

There remains some uncertainty as to the full impact of the mechanical ventilation on indoor humidity, since the experimental protocol imposed 100- and 300-hour on/off periods may have prevented these impacts from being fully expressed. But overall, the data tend to support the contention of Glass and TenWolde time lags in indoor humidity due to moisture storage are on the order of days.[13] This suggests that the humidity impacts we observed based on 100- and 300-hour operating periods represent the majority of the impact that would be seen with continuous operation.

Overall, the humidity data suggest it should not be assumed installation of mechanical ventilation at ASHRAE 62.2 levels would eliminate humidity issues. In some homes, higher mechanical ventilation rates will be needed to deal with higher-than-average moisture loads.

[13] Glass, Samuel and Anton TenWolde, 2009. “Review of Moisture Balance Models for Residential Indoor Humidity,” paper presented at the 12th Canadian Conference on Building Science and Technology, Montreal Quebec, 2009.

The fact CO_2 levels remained above ASHRAE 62.2 ventilation rate equilibrium levels in many cases, despite showing clear reductions when the mechanical ventilation was enabled, may have to do with a combination of poor mixing of indoor air and the non-targeted nature of fresh air induced by exhaust-only ventilation. We provide a short analysis of the former in Appendix C. We found the “forced-on” operation of the furnace air handler noticeably lowered CO_2 levels in several of the monitored sites when mechanical ventilation was **not** enabled, most likely by way of equalizing CO_2 levels across space of varying occupancy. However, this did not carry over when mechanical ventilation was enabled, which could indicate exhaust-only mechanical ventilation may promote better mixing of indoor air.

Monitoring CO_2 levels in rooms with high occupancy density at times (such as bedrooms) may paint an inaccurate picture of whole-home ventilation rates. We concentrated our analysis using sensors located in main living spaces, as these rooms are less likely to be segregated spaces and a better indication of whole-home CO_2 levels. High CO_2 levels in bedrooms does indicate these individual spaces can be inadequately ventilated when they are occupied, even if the home as a whole receives adequate ventilation.

While many homes in the study showed clear evidence of benefiting from the installed mechanical ventilation, some homes did not appear to need mechanical ventilation; despite the fact ASHRAE-62.2 calculations indicated a need for at least 15 cfm of mechanical ventilation. In particular, none of the seven homes with approximately 30 cfm or more of estimated natural ventilation per occupant had high humidity or CO_2 levels, which would indicate inadequate ventilation. It seems that some combinations of 62.2 inputs (square footage, occupancy, and estimated natural ventilation rates) yield significant calculated mechanical ventilation requirements even though substantial natural ventilation is present.

The study results suggest the program could reasonably reduce the installation rate of mechanical ventilation somewhat by only installing it when the 62.2 protocol calls for 15 cfm or more of mechanical ventilation **and** the estimated natural ventilation rate is less than 30 cfm per occupant. Such a screen would help avoid installing mechanical ventilation where it is unlikely to be needed. Since homes with high natural ventilation rates also tend to have a low ratio of 62.2-calculated mechanical ventilation to natural ventilation, which the study data suggest is correlated with the level of impact, this additional screen would help avoid installing mechanical ventilation where it is unlikely to have much incremental effect.

Five of the homes in the study (16%) exceeded the 30-cfm-per-occupant threshold, and two additional homes were borderline, at 29.5 cfm per occupant. However, data on 173 program homes from an earlier 62.2 pilot project suggests that implementing such a screen would have a smaller impact on the installation incidence of mechanical ventilation: of the 103 homes calculated to require at least 15 cfm of mechanical ventilation, only 5 (5%) had estimated natural ventilation that exceeded 30 cfm per occupant.

APPENDIX A − Site Characteristics

Table A-1

Occupancy, Building Size and Air Tightness of Study Homes

Site	Building Identifier	Occupants	Floor area (ft^2)	Building volume (ft^3)	Occupancy density (ft^3/person)	Post-Weatherization air leakage (cfm_{50})	Post-Weatherization air leakage (ACH_{50})
1	53720	5	2,286	18,213	3,643	1,135	3.74
2	56712	3	1,804	14,432	4,811	1,347	5.60
3	57555	4	1,143	9,141	2,285	1,060	6.96
4	57558	3	2,224	17,992	5,997	807	2.69
5	59982	2	1,260	8,884	8,884	989	6.68
6	59988	5	2,174	15,736	3,147	1,837	7.00
7	57038	3	2,592	20,413	6,804	1,750	5.14
8	59418	2	3,192	29,288	14,644	870	1.78
9	59699	5	2,210	15,125	3,025	1,006	3.99
10	58677	3	1,938	15,504	5,168	1,040	4.03
11	58683	8	4,066	32,528	4,066	2,080	3.84
12	60179	1	2,325	18,600	18,600	1,242	4.01
13	60218	4	1,920	15,360	3,840	1,137	4.44
14	60413	1	2,016	16,128	16,128	1,092	4.06
15	62025	5	1,876	15,008	3,002	1,245	4.98
16	62176	5	1,760	14,080	2,816	903	3.85
17	59038	4	1,836	14,688	3,672	1,401	5.72
18	59789	7	2,340	18,720	2,674	2,358	7.56
19	57026	2	2,688	22,848	11,424	1,010	2.65
20	58362	5	3,360	26,880	5,376	2,134	4.76
21	W0118	5	2,342	19,316	3,863	790	2.45
22	W0120	2	2,019	16,479	8,240	1,140	4.15
23	W0124	4	3,124	25,092	6,273	2,005	4.79
24	W0133	4	2,080	15,776	3,944	2,000	7.61
25	54612	2	2,652	18,564	9,282	1,314	4.25
26	56162	6	2,570	21,305	3,551	1,900	5.35
27	56265	2	1,617	12,777	6,389	1,085	5.10
28	58256	4	2,591	19,477	4,869	1,714	5.28
29	63193	5	2,557	18,056	3,611	1,330	4.42
30	63731	4	2,150	16,730	4,183	768	2.75
31	65734	5	2,806	22,911	4,582	1,543	4.04
32	W0136	1	2,046	16,081	16,081	683	2.55

Table A-2

Required and Supplied Mechanical Ventilation

Site	ASHRAE 62.2 required mechanical ventilation: Original calculations: Full (cfm)	Infil. credit (cfm)	Req'd (cfm) (A)	Adjusted for change in occupancy at time of monitoring installation: Change in # of occ	Adjusted required cfm (B)	Supplied mechanical ventilation[a]: Operating flow (cfm)	Duty cycle	Effective flow[b] (cfm) (C)	% of 62.2 required cfm: Original C/A)	Adjusted (C/B)
1	60	12	48		48	41	100%	41	85%	85%
2	41	17	24		24	31	100%	31	129%	129%
3	41	15	26		26	36	100%	36	138%	138%
4	37	0	37	1	45	42	100%	42	114%	94%
5	28	12	16		9	16	100%	16	100%	188%
6	59	25	34		34	38	100%	38	112%	112%
7	41	25	16	1	24	47	25%	12	74%	50%
8	47	0	47		47	133	100%	133	283%	283%
9	60	3	57		57	54	100%	54	95%	95%
10	42	9	33		33	58	67%	39	117%	117%
11	101	21	80		80	133	67%	89	111%	111%
12	31	8	23		23	54	58%	32	137%	137%
13	34	12	22	2	37	69	50%	35	157%	93%
14	28	6	22		22	42	50%	21	95%	95%
15	56	11	45		45	65	75%	49	108%	108%
16	63	5	58	-1	51	60	100%	60	103%	119%
17	48	23	25		25	51	50%	26	102%	102%
18	76	46	30		30	81	100%	81	270%	270%
19	42	0	42		42	(see d below)				
20	71	29	42		42	42	100%	42	100%	100%
21	61	0	61		61	51	100%	51	84%	84%
22	35	10	25		25	26	100%	26	104%	104%
23	61	28	33		33	32	100%	32	97%	97%
24	51	30	21		21	32	100%	32	152%	152%
25	42	9	33		33	32	100%	32	97%	97%
26	71	27	44		44	45	100%	45	102%	102%
27	31	11	20		20	24	100%	24	120%	120%
28	56	16	40		40	42	100%	42	105%	105%
29	63	8	55		55	64	83%	53	116%	97%
30	52	-1	53		53	49	100%	49	92%	92%
31	66	-1	67	-2, e	67	67	100%	67	100%	100%
32	28	0	28		28	30	100%	30	107%	107%

[a]Measured at the time of monitoring installation, after attempted adjustment to match the original 62.2 required mechanical ventilation.

[b]Calculated as operating flow * duty cycle percent/100. (Although ASHRAE 62.2 also includes a ventilation effectiveness factor for intermittent operation with off periods of more than 3 hours, all of the units in the study cycled on an hourly basis.)

[c]Measured flow not available at this time.

[d]Installation problems with the study controller rendered the mechanical ventilation inoperable for the monitoring period.

[e]Ventilation rates did not appear not appear to be adjusted for change in occupancy.

APPENDIX B − Data Compilation and Review

A number of steps were required to compile and process the data from each set. First, because some of the data loggers were field launched, and because the loggers used various sampling rates, the sampling times for the various loggers frequently did not match up. Data from these fixed-interval loggers were imported into a master one-minute level template, and interpolated values were calculated for minutes between actual samples. The compiled one-minute data stream was then averaged down to the hourly level. Similarly, time-stamp data from the on/off status loggers was converted to hourly fractional on-times and merged with the other time series data.

We also merged in hourly Automated Surface Observing System (ASOS) weather data from nearby airports.[14] The weather data we used included temperature, dew point, and barometric pressure.

We used standard psychometric calculations to convert measure temperatures and relative humidities (or dew points) into absolute humidity levels based on the hourly barometric pressure data and the approximate elevation of each site.

We examined time series charts of bedroom and living room CO_2 levels in order to identify and segregate periods of extended absences. We used temperature data from the probe above kitchen ranges to help segregate CO_2 pulses associated with range use. Finally, we examined CO_2 data collected during round two for events where indoor CO_2 levels rapidly equilibrated with outdoor levels, which often indicated residents opening windows to directly ventilate with outdoor air. These events were identified and segregated from the rest of the data.

Finally, we merged datasets from each of the two monitoring periods into one complete dataset.

Most of the analysis in this report is based either on the hourly data compiled per the methods above, or on daily data derived from means, medians, minimums, and maximums of the hourly data.

Though most of the data collected at the end of Rounds 1 and 2 appear to be valid and useful, there were some data issues, particularly with CO_2 sensors being unplugged. Site-specific data issues in the two rounds of monitoring are documented in Tables B-1 and B-2.

Four sites bear particular mention:

Site 8

Installation of the study timer on the ERV at Site 8 proved problematic, since the timers were built for the simpler wiring of exhaust fans. A Grasslin timer programmed to operate the unit from noon on Monday through noon on Thursday was installed but did not operate as intended. At the onset of Round 2, the wiring/operation issues affecting the data in Round 1 were corrected, and the unit was disabled periodically in accordance with experimental protocol.

[14] We used data from a NOAA ftp access site at: ftp.ncdc.noaa.gov for the following sites: Appleton, Eau Claire, Lone Rock, Madison, Oshkosh, Rice Lake and Wausau.

Site 17

Fan status data indicated that fan operated within control periods, but may have not cycled at the intended rate. The end-result may be a lower than expected amount of supplied ventilation. The CO_2 data analyzed for this site showed a statistically significant reduction in CO_2 when mechanical ventilation was enabled; however, we do not know whether these reduction would have been greater had the fan cycled as intended.

Site 18

Round 1: The CO_2 sensors and their associated data loggers, which also tracked temperature and humidity in the main living space and master bedroom, were found in a closet at the time of the second site visit. The data from these loggers showed valid CO_2 data for two periods for the main living area (November 21 to December 3, and December 20 to January 5) and one period for the bedroom logger (February 1 to February 9). Temperature and humidity data were recorded by these loggers throughout the period, with humidity values that tracked the bathroom logger closely (except for bathing-related humidity spikes in the bathroom). We used the data recovered from these loggers, though there is some question about when they may have been moved.

Round 2: A large portion of main living area CO_2 data was recovered; however, not much was recovered from the bedroom sensor due to issues similar to those in Round 1.

Site 19

At Site 19, an error in installing the study timer led to burning out the ventilation controller, with the result that there was no mechanical ventilation during Round 1. We retained this site in the analysis, however, as a useful “control” home. The site was removed from the study at the beginning of Round 2.

Table B-1
Round 1 Data Issues

Site	Issue
1	Main living area temperature and humidity sensor data deviate from bedroom and bathroom sensor readings—need to check sensor calibration at conclusion of study.
3	No main living area CO_2 after December 1.
6	Withdrew from study in early December.
8	Unable to install standard study timer. Installed a separate timer to enable system from noon Monday through noon Thursday, but do not have separate tracking of system operation, and data suggest that system may not have operated during Round 1. Also, do not yet have mechanical ventilation flow.
9	No main living space CO_2 for January 8-14.
10	No main living space CO_2 from November through early January.
13	No main living space CO_2 data throughout Round 1.
18	No main living space or master bedroom CO_2 data for much of Round 1. Main living space and master bedroom temperature/humidity loggers may have been moved by occupants.
19	Attempt to install study timer resulted in burning out the ventilation controller: mechanical ventilation therefore did not operate during Round 1.

Table B-2
Round 2 Data Issues

Site	Issue
1	Missing several weeks of main living area CO_2 data.
2	Missing bedroom CO_2 data for significant portions of February and May.
4	Shorter than normal controller “on” periods during first two 300 hr “on” cycles.
5	Missing bedroom CO_2 data for study period.
8	300 hr “on” cycles appear to abbreviated in relation to “off” periods.
9	Missing main living space area CO_2 data for several weeks over study period.
11	Missing main bedroom CO_2 data for several weeks over study period.
16	Missing main living area CO_2 data for a month long period (mostly during April).
21	Missing main living area CO_2 data for sporadic periods (~one month total over study period).
22	Some abbreviated “on” periods (2 at about 50 hrs each).
23	Thermostat sensor data empty, cloned variables from main living space.
25	“On” periods appear to be “100 hr” in length as opposed to “300 hr.”
28	No bedroom CO_2 data for the study period (faulty sensor).
32	“Off” periods appear to be longer than 300 hrs.

APPENDIX C − CO_2 Summary Statistics

Table C-11

Averages of Daily Mean CO_2 Levels and Deltas in Averages of Daily Means for the **Main Living Space** for Periods when Mechanical Ventilation was (was not) Operational

Site	Averages for Daily Mean CO2 Concentrations and Associated Deltas in CO2 Due to the Use of Mechanical Ventilation (MV on/off)							
	Main Living Space							
	Weekdays				Weekend			
	MV on	MV off	Delta*	Delta CI**	MV on	MV off	Delta*	Delta CI**
1	670	772	102	± 39	666	755	90*	± 95
2	1127	1646	518	± 105	844	1254	410	± 100
3	743	1028	285	± 55	816	1029	213	± 97
4	947	1229	281	± 87	934	1233	299	± 148
5	984	1095	111	± 37	966	1122	156	± 60
6	757	828	71*	± 97	683	877	194*	± 207
7	539	570	31	± 30	611	663	52*	± 102
8	557	1082	525	± 60	540	1136	596	± 98
9	682	843	161	± 46	729	975	246	± 49
10	708	1010	301	± 78	766	1198	432	± 179
11	804	984	180	± 68	797	1072	276	± 112
12	407	451	45	± 30	435	493	58	± 40
13	604	1028	424	± 89	779	1343	564	± 167
14	551	569	18*	± 43	489	578	89	± 89
15	1022	1397	375	± 39	1090	1493	403	± 76
16	886	1386	500	± 62	987	1704	716	± 154
17	803	1022	219	± 51	782	1069	287	± 66
18	858	1140	282	± 124	802	1320	518	± 228
19***	807	847	40*	± 44	737	908	171	± 64
20	653	711	58	± 20	671	748	77	± 28
21	1033	1357	324	± 53	1088	1415	327	± 84
22	481	499	18*	± 24	456	474	18*	± 44
23	672	707	35*	± 42	688	745	57*	± 119
24	912	1028	117	± 49	941	1029	88	± 53
25	699	755	56	± 40	800	775	-26*	± 65
26	907	1325	418	± 128	1011	1322	311	± 213
27	685	807	122	± 28	676	852	176	± 62
28	914	1206	292	± 50	958	1246	288	± 97
29	803	1036	233	± 66	943	1017	74*	± 178
30	758	1155	397	± 45	836	1296	460	± 106
31	731	1017	286	± 73	753	1052	299	± 153
32	700	869	168	± 34	708	891	183	± 47

*Not statistically significant. Statistical significance tested on daily means using a two-tailed t-test at a .05 level of significance.

**95% confidence intervals for change in CO2 levels.

***Limited data due to sensor or controller malfunction.

Table C-2

Averages of Daily Mean CO_2 Levels and Deltas in Averages of Daily Means for the Main Bedroom for Periods when Mechanical Ventilation was (was not) Operational

Site	Averages for Daily Mean CO2 Concentrations and Associated Deltas in CO2 Due to the Use of Mechanical Ventilation (MV on/off)							
	Main Bedroom							
	Weekdays				Weekend			
	MV on	MV off	Delta*	Delta CI**	MV on	MV off	Delta*	Delta CI**
1	850	985	135	± 47	921	1042	121	± 71
2	1311	1735	424	± 148	920	1376	456	± 117
3	773	1007	234	± 37	777	1034	257	± 66
4	984	1262	278	± 78	973	1270	297	± 136
5	1184	1227	44*	± 56	1234	1359	125	± 104
6	702	836	134	± 82	696	799	103*	± 211
7	669	725	56	± 41	731	773	42*	± 109
8	695	1191	496	± 55	693	1228	535	± 102
9	718	885	167	± 38	776	1024	248	± 50
10	867	1111	244	± 63	925	1291	366	± 141
11	830	992	161	± 82	808	1063	256	± 130
12	593	718	125	± 46	629	782	154	± 66
13	704	923	219	± 52	879	1300	421	± 102
14	554	568	13*	± 48	485	542	56*	± 107
15	882	1260	379	± 51	908	1326	418	± 73
16	1285	1753	468	± 83	1358	2143	786	± 135
17	884	1117	234	± 52	866	1175	309	± 67
18***	819	1050	231*			1260		
19***	901	931	30*	± 52	834	1009	175	± 71
20	638	692	54	± 18	631	693	63	± 28
21	1084	1418	334	± 51	1170	1479	309	± 88
22	642	674	32	± 23	618	641	23*	± 29
23	893	892	-1*	± 48	890	955	65*	± 145
24	641	746	106	± 63	674	749	76	± 62
25	1180	1255	75*	± 80	1236	1203	-34*	± 126
26	1069	1572	504	± 156	1193	1542	349	± 334
27	693	819	126	± 29	685	856	172	± 66
28***	Sensor fault, no data collected.							
29	885	1134	249	± 73	1019	1095	77*	± 197
30	826	1185	359	± 44	870	1311	441	± 102
31	740	1037	297	± 71	775	1081	306	± 160
32	710	863	153	± 33	718	875	156	± 52

*Not statistically significant. Statistical significance tested on daily means using a two-tailed t-test at a .05 level of significance.

**95% confidence intervals for change in CO2 levels.

***Limited data due to sensor or controller malfunction.

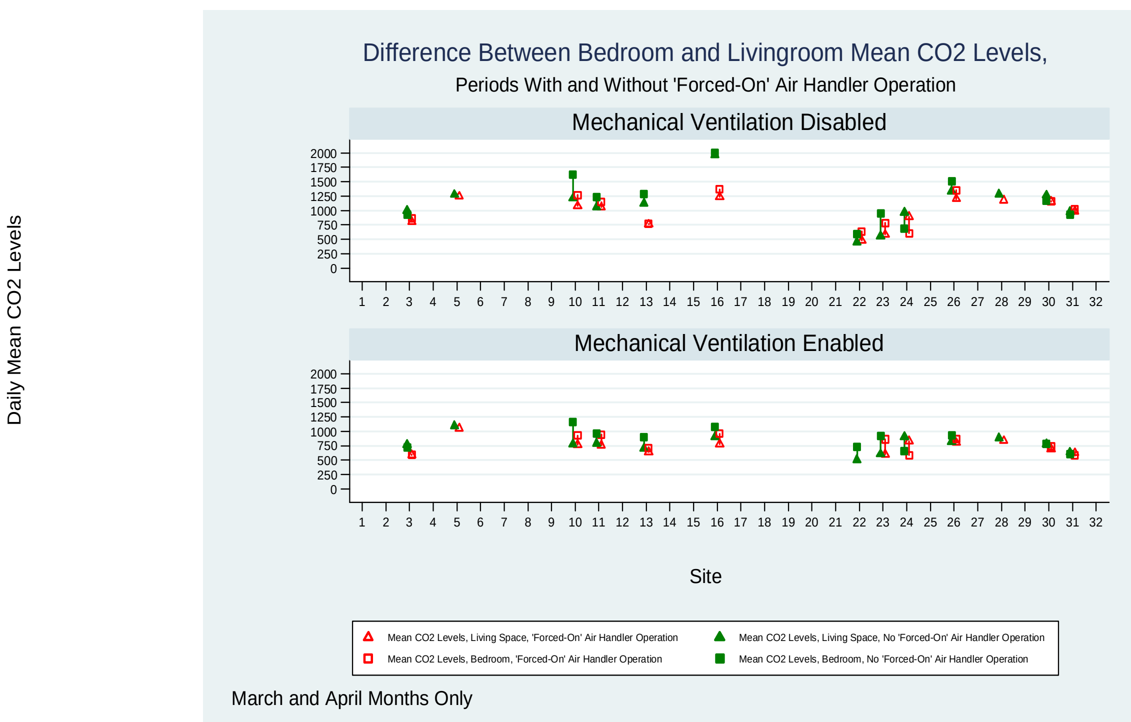
APPENDIX D − Analysis of Mixing

CO_2 Levels During Periods of "Forced-ON" Air Handler Status

As mentioned in the body of the report, some residents allowed for programmable controllers wired to their furnace air handlers. Controllers were programmed to force the air handler to run during specified time periods. The air handler was allowed to run outside of these periods when called by thermostat.

We examined individual air handler run charts to assess whether controllers were indeed forcing furnace blowers to operate during prescribed time periods (typically for three hours during the late evening or early morning hours, two or three days during the week). Accordingly, we selected a portion (13 sites) where the air handler controller appeared (at least by way of the collected data) to operate as intended. Figure D-1 shows mean daily CO_2 levels for the living room and main bedroom. We limited the data to March and April, as these months typically have heating loads, which are lighter than those of the early and mid-winter months. Doing so allows for evaluation of "forced-on" air handler operation (during the prescribed times—typically three-hour blocks on 2 or 3 days during the week) against the same periods on days when the air handler can be expected to be operating on a more seldom basis (due, once again, to the lighter heating loads during the months of March and April). Segregating data from these months also attenuates the added impact of "stack-effect" driven natural ventilation, which we would expect to be more prevalent during the dead of winter, when outdoor temperatures are at their lowest.

Figure D-1
Mean CO_2 Concentrations, by Room and Air Handler Status



The green and red bars in Figure D-1 represent the difference in CO_2 levels between the main living space and bedrooms, with and without “forced-on” air handler operation **and** with and without mechanical ventilation, respectively. The top panel in Figure D-1shows using an air handler without mechanical ventilation reduced CO_2 levels in monitored rooms, simply by virtue of equalizing CO_2 levels across rooms with varied levels of occupancy. Only six of the sites in Figure D-1 acknowledged using night or day thermostat setbacks: Sites 3, 11, 23, 26, 30, and 31. Thermostat setbacks, by way of limiting furnace air handler operation, may lead to poorer mixing of indoor air. However, this phenomenon did not seem to have manifested itself in Figure D-1, the homes where owners admitted to using setbacks do not exhibit either: 1) significant variation in CO_2 levels between periods of “forced-on” and “no forced-on” air handler operation; or 2) large differences between living room and bedroom (mean) CO_2 levels.

The bottom panel of Figure D-1 shows that there is little difference in (mean) CO_2 levels, whether or not a furnace air handler is forced to run **when** mechanical ventilation is operational. As such, the bottom panel in Figure D-1 may indicate that mechanical ventilation, in addition to lowering mean CO_2 levels in the monitored rooms, may aid in mixing air throughout the home.

APPENDIX E – Humidity Regression Analysis

We analyzed the impact of mechanical ventilation on indoor humidity with regression analysis in order to minimize the confounding effects of outdoor temperature and humidity, which strongly influence indoor humidity, and isolate the impact of the mechanical ventilation. Prolonged unoccupied periods (as indicated by the CO_2 data) affected indoor humidity: We sought to control for these effects as well.

In addition, preliminary analysis showed there is substantial day-to-day serial correlation in the time series of indoor humidity. That is, indoor humidity on a given day is related to indoor humidity on prior days, even after adjusting for the effects of weather and the other modeled factors. We therefore employed an auto-regressive integrated moving-average (ARIMA) specification. In particular, review of the auto-correlation and partial auto-correlation plots strongly suggested an AR(1) process, in which humidity on a given date is partly predicted by the model residual from the prior day.

We explored a number of alternative model specifications involving various predictors and autocorrelation specifications, and found the estimated mechanical ventilation impact was not particularly sensitive to the model specification. This suggests the on/off experimental protocol did a reasonably good job of controlling for confounding influences between periods when the mechanical ventilation operated and when it was disabled by our timers. The main purpose of the regression modeling is therefore to reduce the amount of unexplained variance, and thus produce more precise estimates of the impact of mechanical ventilation on indoor humidity. Its secondary purpose was to allow us to normalize indoor humidity across sites for outdoor conditions in order to facilitate comparison across sites.

Our final model specification is as follows:

$$H_{in,\,t} = \beta_0 + \beta_1 T_{out,\,t} + \beta_2 H_{out,\,t} + \beta_3 S_t + \beta_4 A_t + \rho\mu_{t-1} + \varepsilon_t$$

Where

$H_{in,\,t}$ = daily average indoor absolute humidity (grains/lb.) for date *t*

$T_{out,\,t}$ = daily average outdoor temperature (F) for date *t*

$H_{out,\,t}$ = daily average outdoor absolute humidity (grains/lb.) for date *t*

S_t = fraction of the day that the mechanical ventilation operated on date *t*

A_t = fraction of the day that the home was unoccupied on date *t* as part of a prolonged absence as evidenced by low CO2 readings.

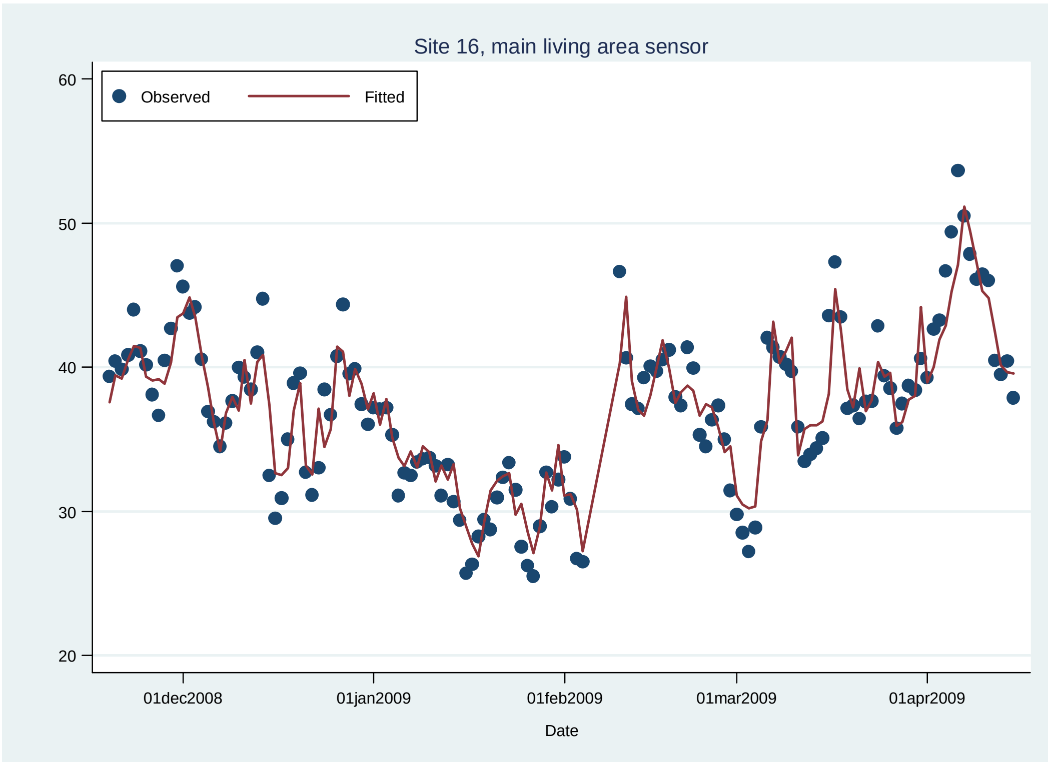
$\mu_{t-1} = H_{in,\,t-1} - (\beta_0 + \beta_1 T_{out,\,t-1} + \beta_2 H_{out,\,t-1} + \beta_3 S_{t-1} + \beta_4 A_{t-1})$

ε_t = residual noise component

The model does a reasonably good job of tracking daily indoor humidity, as can be seen in **Error! Reference source not found.** below.

Figure E-1

Example of Regression Fit to Daily Humidity Data



Regression coefficients and standard errors for all sites and sensors are shown in Table E-2. Coefficient β_3 is of primary interest, as it represents the estimated reduction in indoor humidity when the mechanical ventilation is operated.

Table E-2

Humidity Regression Model Coefficients and Standard Errors (se)

Site	Sensor†	n	β_0	se β_0	β_1	se β_1	β_2	se β_2	β_3	se β_3	β_4	se β_4	ρ	se ρ
1	Lv	149	22.3	1.1	0.092	0.037	0.185	0.055	-1.90	0.57	-2.72	1.57	0.830	0.045
1	bd	149	32.6	2.1	0.056	0.044	0.105	0.069	-1.95	0.72	-5.50	1.33	0.922	0.026
1	ba	149	28.9	1.7	0.078	0.071	0.251	0.123	-3.59	1.43	-7.00	3.70	0.757	0.056
2	Lv	150	34.5	1.4	0.123	0.062	0.205	0.109	-3.00	1.07	-7.20	1.73	0.704	0.056
2	bd	150	35.2	1.5	0.130	0.071	0.181	0.119	-2.23	1.14	-3.94	2.02	0.746	0.052
2	ba	150	35.9	1.5	0.123	0.076	0.191	0.134	-4.12	1.18	-7.02	1.59	0.719	0.059
3	Lv	152	34.0	2.1	0.070	0.035	0.258	0.060	-4.51	0.57			0.937	0.026
3	bd	152	32.7	3.3	0.072	0.053	0.256	0.082	-5.75	0.69			0.948	0.027
3	ba	152	38.9	2.2	0.095	0.052	0.192	0.095	-5.76	0.61			0.896	0.035
4	lv	151	42.5	1.7	0.020	0.034	0.190	0.056	-3.23	0.60			0.900	0.031
4	bd	151	42.8	1.4	0.035	0.031	0.176	0.052	-3.32	0.49			0.901	0.034
4	ba	151	46.7	1.7	0.035	0.042	0.218	0.070	-4.66	0.72			0.870	0.033

Site	Sensor†	n	β_0	se β_0	β_1	se β_1	β_2	se β_2	β_3	se β_3	β_4	se β_4	ρ	se ρ
5	lv	146	39.5	1.1	0.169	0.052	0.080	0.091	-2.10	0.85			0.679	0.058
5	bd	146	41.9	1.1	0.157	0.044	0.030	0.068	-1.29	0.58			0.816	0.042
5	ba	146	34.6	1.0	0.149	0.042	0.111	0.065	-1.86	0.57			0.816	0.037
6	lv	30	28.3	8.7	0.483	0.258	-0.088	0.227	-1.44	2.16	-2.81	1.64	0.916	0.161
6	bd	30	30.5	7.5	0.466	0.228	-0.089	0.198	-1.71	3.81	-3.48	1.62	0.889	0.165
6	ba	30	32.1	13.2	0.641	0.667	-0.086	0.517	-5.44	4.43	-6.25	4.24	0.533	0.398
7	lv	105	24.6	1.6	0.097	0.039	0.131	0.059	0.35	0.52	-1.59	2.54	0.897	0.046
7	bd	105	25.4	1.8	0.081	0.039	0.138	0.058	0.59	0.51	-2.19	2.52	0.908	0.047
7	ba	105	25.5	1.1	0.159	0.046	0.050	0.077	0.26	0.73	-3.24	4.16	0.754	0.071
8	lv	147	48.6	1.8	0.095	0.051	0.112	0.054	-7.58	1.33			0.825	0.050
8	bd	147	51.7	1.8	0.131	0.051	0.092	0.056	-9.56	1.51			0.813	0.054
8	ba	147	54.1	1.8	0.133	0.061	0.089	0.069	-10.0	1.82			0.746	0.066
9	lv	137	22.7	1.1	0.078	0.033	0.361	0.040	-2.34	0.51			0.788	0.047
9	bd	137	22.3	1.1	0.113	0.035	0.326	0.042	-2.76	0.54			0.760	0.050
9	ba	137	22.4	2.1	0.442	0.089	0.240	0.123	-2.40	1.46			0.248	0.084
10	lv	145	35.9	1.8	0.103	0.043	0.077	0.046	-3.51	0.57			0.896	0.040
10	bd	145	39.5	2.0	0.108	0.043	0.022	0.046	-3.20	0.60			0.908	0.034
10	ba	145	37.4	1.8	0.096	0.050	0.090	0.053	-3.94	0.68			0.878	0.043
11	lv	110	28.4	1.9	0.088	0.032	0.190	0.037	-1.52	0.45			0.932	0.032
11	bd	110	31.2	1.6	0.068	0.036	0.090	0.043	-1.09	0.55			0.893	0.043
11	ba	110	32.0	1.4	0.171	0.058	0.095	0.078	-3.29	0.94			0.668	0.071
12	lv	111	27.4	3.8	0.093	0.038	0.087	0.041	-0.64	0.54	-1.31	0.57	0.968	0.022
12	bd	111	30.8	2.6	0.055	0.040	0.082	0.049	-0.55	0.64	-2.28	0.62	0.940	0.029
12	ba	111	31.4	2.5	0.065	0.044	0.064	0.056	-0.69	0.65	-2.80	0.67	0.932	0.033
13	lv	143	27.0	1.3	0.228	0.047	0.013	0.059	-2.20	0.79			0.721	0.063
13	bd	143	28.6	1.3	0.233	0.048	0.022	0.062	-2.12	0.83			0.705	0.064
13	ba	143	32.3	1.4	0.276	0.066	-0.001	0.085	-3.63	0.93			0.636	0.067
14	lv	73	31.5	11.1	0.002	0.066	0.257	0.080	-0.61	0.55	-1.19	1.80	0.983	0.038
14	bd	73	34.5	12.1	-0.031	0.057	0.248	0.059	0.26	0.57	-1.02	1.91	0.989	0.025
14	ba	73	32.5	10.6	0.005	0.044	0.267	0.056	-0.47	0.46	-1.17	1.14	0.989	0.027
15	lv	112	32.5	1.1	0.117	0.039	0.122	0.045	-2.59	0.63			0.735	0.073
15	bd	112	33.8	1.1	0.123	0.038	0.108	0.042	-1.88	0.60			0.750	0.068
15	ba	112	34.8	1.1	0.130	0.035	0.093	0.041	-2.59	0.64			0.732	0.072
16	lv	143	34.1	1.2	0.073	0.038	0.172	0.046	-3.07	0.57			0.848	0.040
16	bd	143	35.0	1.3	0.089	0.036	0.156	0.048	-3.06	0.64			0.849	0.041
16	ba	143	39.6	2.1	0.208	0.077	-0.001	0.095	-9.72	1.37			0.723	0.051
17	lv	144	31.6	1.0	0.161	0.056	0.262	0.082	-3.66	0.80			0.742	0.064
17	bd	144	33.5	0.9	0.175	0.053	0.197	0.079	-3.53	0.79			0.747	0.067
17	ba	144	34.8	1.0	0.227	0.068	0.222	0.106	-6.22	0.92			0.595	0.076
18	lv	144	29.6	1.8	0.123	0.072	0.410	0.125	-4.21	1.05			0.822	0.053
18	bd	81	26.1	2.7	0.087	0.128	0.420	0.205	-2.90	1.51			0.811	0.083
18	ba	144	32.5	2.2	0.126	0.079	0.314	0.127	-4.60	1.24			0.828	0.052
19	lv	84	35.6	1.4	0.363	0.116	-0.018	0.182	0.99	1.14			0.357	0.128
19	bd	84	37.7	1.9	0.145	0.076	0.139	0.114	1.12	0.72			0.829	0.085
19	ba	84	38.4	2.1	0.114	0.074	0.178	0.111	1.01	0.70			0.867	0.077
20	lv	153	26.3	2.9	0.028	0.039	0.345	0.047	-0.87	0.55			0.946	0.018
20	bd	153	25.4	1.4	-0.008	0.040	0.308	0.055	-0.72	0.62			0.874	0.031

Site	Sensor†	n	β_0	se β_0	β_1	se β_1	β_2	se β_2	β_3	se β_3	β_4	se β_4	ρ	se ρ
20	ba	153	25.4	1.0	0.045	0.041	0.332	0.053	-0.87	0.67			0.819	0.043
21	lv	154	46.8	1.6	0.121	0.039	0.075	0.048	-2.92	0.57	-0.74	1.68	0.890	0.035
21	bd	154	47.4	1.5	0.146	0.037	0.065	0.045	-2.43	0.60	-1.88	1.32	0.886	0.039
21	ba	154	48.7	1.2	0.110	0.049	0.133	0.064	-5.21	0.79	-4.84	3.16	0.769	0.053
22	lv	134	21.6	3.1	-0.017	0.031	0.314	0.046	-0.75	0.52			0.971	0.019
22	bd	134	22.7	3.4	-0.005	0.027	0.285	0.035	-0.38	0.41			0.975	0.019
22	ba	134	21.4	3.2	0.010	0.036	0.283	0.051	-0.92	0.63			0.964	0.021
23	lv	154	20.2	1.4	0.135	0.039	0.135	0.048	-1.07	0.72			0.829	0.035
23	bd	154	23.1	1.5	0.211	0.057	0.072	0.065	-0.66	0.97			0.593	0.057
23	ba	154	22.4	1.9	0.117	0.032	0.062	0.042	-0.30	0.53			0.927	0.025
24	lv	155	37.5	1.6	-0.005	0.074	0.323	0.081	-2.91	1.09	2.79	1.87	0.719	0.051
24	bd	155	38.2	1.8	-0.014	0.074	0.315	0.073	-2.82	1.05	3.21	1.97	0.768	0.047
24	ba	155	44.3	2.5	-0.037	0.123	0.443	0.126	-5.48	2.04	1.35	4.53	0.724	0.027
25	lv	71	23.0	1.3	0.182	0.081	0.166	0.091	-2.60	0.64			0.744	0.105
25	bd	71	27.2	1.6	0.185	0.064	0.072	0.084	-3.04	0.77			0.814	0.078
25	ba	71	28.1	1.8	0.229	0.076	0.052	0.084	-3.38	0.97			0.711	0.106
26	lv	57	39.3	2.3	0.191	0.067	0.045	0.059	-2.58	1.32	-7.69	2.43	0.643	0.117
26	bd	57	42.0	2.3	0.119	0.077	0.089	0.064	-1.92	1.71	-9.36	2.49	0.748	0.105
26	ba	57	41.8	3.0	0.276	0.091	0.000	0.108	-4.47	1.97	-11.60	3.32	0.565	0.136
27	lv	70	24.9	1.7	0.131	0.052	0.155	0.066	-1.13	1.05			0.887	0.058
27	bd	70	24.1	1.7	0.143	0.055	0.160	0.067	-1.28	1.17			0.867	0.065
27	ba	70	25.5	1.8	0.197	0.070	0.114	0.087	-1.63	1.45			0.797	0.083
28	lv	69	36.8	4.1	0.156	0.135	0.148	0.126	-2.73	2.97			0.872	0.049
28	bd	69	39.4	4.0	0.222	0.200	0.174	0.261	-3.18	5.16			0.750	0.059
28	ba	69	39.2	3.0	0.218	0.120	0.175	0.133	-4.35	3.15			0.639	0.061
29	lv	57	31.8	2.0	0.126	0.055	0.106	0.056	-1.18	0.97			0.738	0.117
29	bd	57	31.5	2.3	0.159	0.068	0.127	0.075	-0.95	1.17			0.625	0.145
29	ba	57	31.9	2.5	0.156	0.070	0.081	0.076	-0.73	1.32			0.692	0.127
30	lv	63	34.1	1.4	0.150	0.050	0.004	0.058	-2.68	0.85			0.766	0.072
30	bd	63	32.8	1.3	0.090	0.040	0.112	0.038	-1.90	0.98			0.812	0.072
30	ba	63	38.9	1.8	0.217	0.060	0.004	0.067	-5.71	1.12			0.539	0.113
31	lv	57	35.7	2.0	0.269	0.082	-0.014	0.101	-1.63	1.32			0.616	0.109
31	bd	57	37.7	1.9	0.235	0.070	0.014	0.093	-1.51	1.24			0.666	0.106
31	ba	57	37.9	2.0	0.257	0.082	0.016	0.098	-2.20	1.32			0.576	0.114
32	lv	72	23.1	1.3	0.190	0.047	0.054	0.055	-2.05	1.22			0.877	0.063
32	bd	72	22.0	1.3	0.161	0.043	0.056	0.049	-1.54	1.47			0.897	0.059
32	ba	72	22.7	1.3	0.211	0.052	0.030	0.063	-2.34	1.17			0.837	0.072

†lv = main living area sensor; bd = master bedroom sensor; ba = bathroom sensor

We also examined whether there is a time trend component associated with the amount of time the mechanical ventilation was operated (or disabled). The purpose of this analysis was to assess the extent to which the experimental protocol that periodically disabled the mechanical ventilation prevented the full effect on indoor humidity from manifesting.

We approached this task by examining the model residuals as a function of the amount of time the mechanical ventilation had either been operating or had been disabled. If a significant amount of time is required for mechanical ventilation to fully effect indoor humidity, then we would expect to see a pattern of decreasing residuals when the mechanical ventilation was enabled, and a pattern of increasing residuals over time when the mechanical ventilation was disabled. Because we were concerned that the auto-regressive component of the model might mask any such trend, we examined the residuals both for the ARMAX model above and an ordinary least squares (OLS) model that omitted the AR(1) term.

The results suggest that there is some basis for this concern (Table E-3). While the residuals slopes are about evenly divided between negative and positive directions for the ARMAX model (and few are statistically significant), for the OLS model, more than three quarters of the cases show a negative slope to the residuals when the mechanical ventilation is operated, and 60 percent show a positive slope when it is disabled—just as one would expect if the effect of enabling or disabling the mechanical ventilation builds over time. Moreover, the slope of the residuals is statistically significant in about third to a half of the cases where the slope is in the expected direction.

However, when we included terms in the ARMAX model to explicitly capture the elapsed time of the on/off cycles, there was no consistent impact in the estimates of the impact of the mechanical ventilation on indoor humidity, and only a small (15 percent) average difference. All of this suggests the base model may somewhat underestimate the full impact of mechanical ventilation on indoor humidity at some sites, but the data and experimental design preclude reliably gauging the magnitude of this bias.

Table E-3

Summary Statistics of Regressing Model Residuals on within-cycle Mechanical Ventilation Operating (or disabled) Time, by Model and Mechanical Ventilation Status

		Residuals Show Negative Slope		**Residuals Show Positive Slope**	
Model	**Mechanical Ventilation Status**	% of cases	% where slope is stat. sig.	% of cases	% where slope is stat. sig.
ARMAX	Disabled	51%	4%	49%	13%
	Enabled	47%	2%	53%	2%
OLS	Disabled	40%	18%	60%	45%
	Enabled	76%	32%	24%	4%