MONITORED RESIDENTIAL VENTILATION BEHAVIOR: A SEASONAL ANALYSIS

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ABSTRACT

The effects of occupant behavior on residential energy consumption are known to be significant. In Michigan, where space heating consumes the largest share of residential energy, occupant behaviors influencing energy consumption were monitored by automatic data recorders. The day-to-day occupant behaviors likely to impact space heating energy consumption are thermostat setting and the opening and closing of doors and windows.

While thermostat setting has been the topic of much study, ventilation behaviors have received very little attention. The idea that occupant behaviors significantly affect energy consumption implies that the operation of doors and windows could result from a number of factors and directly influence space heating energy consumption. This implication conflicts with the assumption that intentional window and door use is only a minor contribution to overall winter ventilation and that window openings are directly related to exterior temperature.

This paper presents a seasonal analysis of window and door use to test the above assumptions by relating ventilation behaviors to interior and exterior temperatures and the operation of the thermostat and furnace. While window and door openings are indeed found to be infrequent in winter, seasonal variation in ventilation behaviors is significant such that the rate of air movement through houses (and its effects on energy consumption and occupant health) changes at different times of year. The variation in ventilation behaviors among households is also substantial.

Models of window and door openings and of interior temperature are tested. Ventilation behaviors are found to have their greatest effect on interior temperature during warm weather, but their largest effect on energy consumption appears to be during the spring. Despite the strong effects of exterior temperature, the effects of other variables during some seasons are also of great importance. Ventilation behaviors in locations with significant seasonal changes cannot, therefore, be understood solely as a function of exterior temperature.

MONITORED RESIDENTIAL VENTILATION BEHAVIOR: A SEASONAL ANALYSIS[1]

INTRODUCTION: Why study ventilation behavior?

Research concerning energy conservation in the residential sector has focused on the performance of building structures and major appliances. We have by now a good idea of how the physical structures of houses and the efficiency of appliances affect energy consumption. Less well understood are the effects of occupants on energy consumption in residences, but studies have shown that they have significant impact on energy consumption. The Princeton Twin-Rivers study estimated that only 46% of the variation in space heating energy consumption among the sample of identical townhouse units was accounted for by building structural variables and attributed 71% of the remaining variation to occupant effects (Socolow, 1978:228).

In Michigan space heating consumes the most energy in residences. The effects of thermostat manipulation on energy consumption have been the object of a great deal of study and are known to be very important. The only other day-to-day occupant behaviors which might have a significant impact on space conditioning are the manipulation of doors and windows. The idea that occupant behaviors significantly impact energy consumption implies that manipulation of windows and doors for a variety of factors (maintenance of indoor air quality, control of humidity, entrance/egress, security, poor management, sleeping habits, health concerns, presence of children or of pets as well as maintenance of interior temperature) may vary widely and affect the ways households consume space heating energy.

While in the last few years research has been done regarding the effects of unintentional ventilation on energy consumption and occupant health, it has focused almost exclusively on the physical characteristics of dwellings. Ventilation has been approached primarily as a function of the specific leakage area of houses and measured by blower door or tracer gas tests. Blower door and other ventilation tests are performed with doors and windows closed and measure only ventilation related to building structure. Ventilation behaviors have been virtually unstudied.

Thus recent research has focused on nonoccupant related ventilation. This type of ventilation has been characterized as unintentional, wasteful, and as causing discomfort. Occupant ventilation behavior, by contrast, is understood to be an entirely intentional response to interior conditions of temperature or air quality.

Engineers have considered the contribution of door and window openings to total winter ventilation (and space heating energy consumption) to be minor. This assumption, due to the lack of data regarding actual occupant effects is based mainly on intuition or estimation (Morrill, 1986). Since window openings have been characterized as entirely intentional, occupant ventilation behavior has been seen as a way to manage interior temperature. It would be expected then that window and door openings will occur when interior spaces need to be cooled, and that windows and doors will be closed when interior spaces are heated. This perspective implies that ventilation behaviors during the heating season will be well managed by occupants and that ventilation for reasons unrelated to temperature control will be insignificant.

The assumption that window and door openings are minor contributions to winter ventilation and the assumption that occupant behaviors have great impacts on energy consumption have contradictory implications. This analysis is intended as a first step in answering questions related to these assumptions:

1. Is ventilation behavior primarily a response to and determined by exterior temperature? If not, what models work best at explaining door and window openings?

2. In a climate with an extensive heating season, do window and door openings occur coincidentally with interior space heating? Or are they negligible in the winter and contribute little to heat loss?

3. Since door openings have been little studied, do door and window openings appear to be similar or different phenomena (and if different, how)?

BACKGROUND

Although door opening behaviors have been little studied, some work has been done to understand window use. Conan (1982) analyzed residential window opening behaviors in 113 English residences in two "local authority estates" using systematic window observations. He found that variability between households was greater than was variability within households. Significant relationships between window opening frequencies in different room types indicated that residents consistently adopted "general window opening levels" (3.4). Weather variables were also shown to have significant effects on window opening. External air temperature had by far the greatest effect, but significant correlations were found between some window openings and relative humidity, windspeed and duration of sunshine.

Warren and Parkins (1984) reported on window use in five English office buildings. Ninety observations were made regarding the open/closed status of windows on each building's facade. Again window openings were found to be strongly associated with external air temperature (accounting for 76% of observed variance). Additionally, larger windows were more closely associated with temperature than were smaller, suggesting that smaller windows were more often used to regulate indoor air quality.

Dick and Thomas (1951) studied window openings in two sets of houses in post-war England. They found that external air temperature accounted for 70% of observed variance and that an additional 10% was accounted for by wind-speed.

DESCRIPTION OF STUDY

Window and door opening measurements were part of an instrumentation package installed in seven houses in the mid-Michigan area to measure energy related occupant behaviors (Weihl, et al., 1983). These houses were selected for diversity of house type and occupants. Micro data-loggers recorded exterior temperature, thermostat setting, various interior temperatures, door and window open-times and furnace run-time. Data were outputted in hourly and daily summary forms. Door and window openings were measured using magnetic reed switches. All exterior doors and a small sample of windows (usually 1-3 per house) were monitored. Windows were chosen for instrumentation by asking residents which they used most often. The instruments could not determine how many doors or how many windows were open simultaneously, nor could they determine which individual doors or windows were opened or closed.

DESCRIPTION OF DATA

Due to instrumentation schedules and technical problems, data collection periods for each house do not necessarily coincide and the data are of varying quantity and quality among houses. Table I details the data collection at each house. The data for house #7 is split, since during the sampling period the occupants of the house changed. References to family 7A and 7B refer to this change of occupancy.

RESULTS

Because of the large amount of data collected, daily summaries of hourly variables rather than the hourly data themselves were used in most analyses. Daily summaries are much easier to manipulate, and several checks showed that they accurately reflected the hourly data. Analyses requiring the use of hourly data are noted. Analyses were performed on microcomputers using a statistical programming language package. When data are analyzed by season, seasons are defined as: Spring (16 Mar. to 15 June), Summer (16 June to 15 Sep.), Fall (16 Sep. to 15 Nov.), and Winter (16 Nov. to 15 Mar.).

Differences Between Families

Comparing the variable means for each family and the variable means for the sample as a whole (Table II) demonstrates the large differences evident in window and door opening behaviors. Since different amounts of data were collected for each house, and since data were not distributed evenly across seasons, sample means are weighted toward some families and case means are weighted toward some seasons.

Comparing means shows two interesting results. First, there was a precisely defined level of interior temperature or comfort level (72°F) with very little variance. Second, there were very large differences between households in ventilation behaviors. The household with the largest mean door open-time (#6) had a mean four times larger than that of the family (#5) with the smallest mean. In window openings (excluding family 2)[2] the difference is even greater (8 to 1). It is clear that there are significant differences in voluntary ventilation behavior among families. The data also indicate that window opening behavior differs more among families than does door opening behavior.

Seasonal Ventilation Behavior Characteristics

Table III shows the seasonal variation in means for the entire sample. The data support the idea that window and door open-times are related to exterior temperature. Door and window open-times are longer in the summer and spring when the exterior temperature is warmer. During the winter, spring, and fall, door open-times are greater than window open-times. In the summer, however, window open-time increses dramatically and is greater than door open-times. Since doors also serve other functions than do windows (entrance, egress, nighttime security), it makes sense that door openings are less temperature dependent than are window openings. Still, the large seasonal differences in door open-time indicate that doors are often used for ventilation purposes during warm weather.

Since Michigan has a long heating season which begins in fall and ends well into spring, the data indicate that there may be significant cool weather ventilation. Window and door use in the very cold winter is small yet still nontrivial since windows are open 2.7% of the time and doors are open 6% of the time.

Correlations

An examination of the correlations between variables will show how well we can expect window and door openings to vary with exterior temperature, interior temperature, thermostat setting, and each other. Pearson's correlation coefficient matrices were produced for the sample as a whole and for each season. The results are presented in Tables IV-VI.

For the sample period as a whole (Table IV) both window and door openings had strong positive and significant (at .05) correlations with exterior temperature, indicating that longer window and door open-times occur with higher exterior temperature. Both window and door openings showed significant and moderate inverse relations to thermostat setting and furnace run-time. Thus ventilation behaviors generally take place when the thermostat is lowered and when the furnace runs less often. Correlations between interior temperature and door and window openings were generally weaker (but still significant at .05), probably due to the comparatively small variation in interior temperature. As expected, ventilation behavior is more likely to occur with higher indoor temperature. Window and door openings show only a weak to moderate correlation with each other.

During the winter (Table V), window and door open-times show virtually no relationship with exterior or interior temperature, thermostat setting, furnace run-time or each other. This indicates that door and window openings during winter are (in addition to being less frequent) related not to occupant control of interior temperature but to other functions such as entrance/egress or indoor air quality.

During the summer, exterior temperature shows a large correlation with window open-time but a weak inverse relationship with door open-time. This indicates that window opening is an important method of summer cooling (none of the sample households have air-conditioning), but that door opening does not increase with exterior temperature in the summer. Door and window openings show no correlation with each other during the summer. Clearly, window opening is related to summer cooling while door opening seems to be driven by other factors.

During the spring (Table VI), window opening again shows a strong positive relationship with exterior temperature but door openings show an even stronger relationship. Unlike summer, door openings in the spring <u>do</u> seem to be related to cooling. In fact, door open-time correlates with interior temperature better than any variable with the exception of exterior temperature, suggesting that door openings may be more important than window openings for spring cooling. Door and window openings correlate moderately well with each other in the spring and better than they do in any other season.

Fall window and door use correlate only weakly with exterior temperature. Interior temperature correlates slightly better with window openings but in an inverse manner, while it has no relationship with door opening. It is unclear why window open-time increases with lower interior temperatures, unless holdover summer window opening patterns (frequent, long open-times) occur and result in lower interior temperatures than is desirable. Both window and door open-time have moderately strong inverse relationships with thermostat setting indicating that window and door openings are probably longer in the early fall when thermostat settings are low and shorter in the late fall when thermostat settings rise dramatically. As in spring, door and window openings correlate with each other to a moderate degree, suggesting that door opening patterns are more likely to resemble window opening patterns in the transitional seasons, spring and fall, than in winter and summer.

Ventilation Behaviors and Space Heating

The idea that occupant behaviors such as thermostat setting and window and door use have significant effects on energy consumption, and the idea that ventilation behaviors are entirely intentional, have somewhat contradictory implications. The former idea implies that occupant management (or lack thereof) of doors and windows might lead to the furnace running while doors or windows are open for ventilation. The latter idea implies that coincidental furnace use and ventilation behaviors will be minimal as the occupant will close windows and minimize door use to conserve heat.

By measuring furnace run-time that overlaps with door and window use, we can see which of these two ideas better reflects occupant behavior. This analysis utilizes the hourly data, rather than daily summary data. The data cannot indicate the precise amount of time that windows and door open-time is coincident with furnace on-time, but does identify each hour that contains both door or window open-time and furnace on-time.

Table VII summarizes the coincidental occurrence of ventilation behaviors and furnace run-time. Coincidental furnace on-time and ventilation behaviors are expressed both as percentages of total door and window open-time and percentages of total hours containing furnace on-time.

The leftmost column shows the percentage of hours containing window open-time that also contain furnace run-time, and gives an approximation of how well occupants manage their ventilation behaviors. Higher percentages reflect either poorer management or higher uses of doors and windows for functions other than temperature control. Percentages range from 0% to 75% (families 7A and 7B) but the mean percentage for entire data set is 6%, indicating that occupant management is fairly good and that most window openings occur when the furnace is not operating.

The percentage of total hours containing furnace use which also contain window openings is reported in the second column. This column is a crude approximation of the relative effect of window opening on heating energy consumption. Ratios range from 0% to 13% with a mean percentage of 2.5%. Thus a relatively small proportion of furnace use occurs when windows are being used. Both columns support the idea that window use has relatively little effect on space heating.

In order to better approximate occupant management of doors and the effects of door opening, the third and fourth columns show the mean number of minutes open per hour rather than percentage of hours containing open-time.[3] The third column shows the mean number of minutes of door open-time per hour (for each hour containing door open-time) for the entire sample period. The fourth column shows the same percentage during hours that also contained furnace run-time. Comparing these two columns gives an approximate indication of change in the duration of door opening events and/or number of door openings per hour. As can be seen, door open-time is normally quite high (28 minutes per hour) and, although it decreases dramatically in hours when space heating occurs (17 minutes per hour), it remains relatively high.

Space heating does occur coincidentally with door and window opening behaviors. However, window openings appear to be managed fairly efficiently during these times. As might be expected, reduction in door open-times during furnace operation is not so complete. In this sample door openings in cold weather probably have a greater effect than window openings on space heating energy consumption. The differences in door open-time indicate, however, that doors are operated differently in the heating season than they are during the rest of the year.

Modeling Door and Window Openings

Since models which predict energy consumption or indoor air quality may be influenced by how they account for the effects of door and window openings, it is important to understand what factors affect ventilation behavior at different times of year. Previous studies have described window opening as a function of external temperature. We have seen that door and window openings vary considerably during different seasons and correlate with each other and other variables quite differently during different seasons. Several questions are thus raised: Are door and window openings primarily functions of exterior temperature? How do interior temperature, thermostat setting and furnace run-time affect ventilation behaviors? Are the factors which influence door openings different from those which drive window openings? How do models for ventilation behavior change in effectiveness and composition during different seasons?

As a preliminary step in answering these questions, linear regression models were calculated using the daily summary data for each household. Window and door open-time were regressed against various combinations of variables to determine which combinations accounted for the most variation in the dependent variable.

For window open-time, the equation including all variables generally performed better than did equations using temperature (interior and exterior) or behavioral (door openings and themostat setting) variables alone. The left side of Table VIII reports the adjusted R^2 values for this equation for each family during each season. Adjusted R^2 values reflect the percentage of the variation in the dependent variable (window open-time) accounted for by the model.[4] An R^2 value of .2500 means that 25% of the variation in the dependent variable can be accounted for in the model. Considering the number of factors that drive human behaviors such as door and window opening (individual preference, family schedules, health, occupant ages, security concerns, humidity, beliefs, etc.), 25% or more accountability for the variation in these behaviors with the monitored variables can be interpreted as meaningful.

Table VIII indicates that for all families the model does not work at all in the winter and works moderately well in the spring, summer, and fall. Still there is considerable variation in the effectiveness of the model between different families. For instance, during the spring the model works exceptionally well for families 3 and 6, while it does not work at all for family 7A. The model accounts for 46% of the fall, 32% of the summer, 27% of the spring, and none of the winter variation. Thus these temperature-related independent variables account for a good share of the variation (30% overall), but there is still a good deal of variation unaccounted for. This suggests that other factors have a great deal of importance in influencing window use.

Table IX shows the proportions of the explained variance accounted for by each of the independent variables. Since during the winter no variance is accounted for by the model, the proportions are not reported. During the spring most variance is accounted for by exterior temperature but thermostat setting and door open-time also account for significant shares. In summer, exterior temperature accounts for the highest proportion of the variance and is by far the most important factor in the model. During the fall, variation in window opening may be better explained by changes in thermostat setting than by exterior temperature. For all seasons, though, exterior temperature and thermostat setting are the most important factors in the equation explaining window open-time.

Door open-time was also regressed against different combinations of independent variables. Again, the equation that was most successful contained all of the independent variables. This equation regressed door open-time against exterior temperature, interior temperature, thermostat setting and window open-time.

The right side of Table VIII shows the relative effectiveness of this model by reporting the adjusted R^2 values for each family by season. Again the model did not work during the winter, with the exception of family 7A. During the spring it was remarkably effective for many households, often accounting for more than half of the variance. During the summer, it was very effective for Family 1, but relatively ineffective for the other families. During the fall, it was moderately effective for most families. For all the families as a group, it was most effective in spring, accounting for 36% of the variance; moderately effective in fall (11%); less effective in summer (7%); and not effective in winter.

Table X shows the relative importance of the independent variables in the equation during the different seasons. As with window openings, no winter variance was explained and no proportions are presented. During the spring, when the model is most effective, exterior temperature accounts for most of the explained variance. In summer, when the model is relatively ineffective, thermostat setting accounts for the most variance. In fall, window open-time has a very strong relative effect while both interior and exterior temperature are relatively weak. In general, the model accounts for about one third of the variance in door opening, with the largest amount of variance accounted for by exterior temperature.

Thus the factors which affect door openings seem to be highly seasonally variable. In the winter, factors unrelated to space heating have the most influence, while during the spring exterior temperature probably has the greatest effect on door openings. In fall and summer, nontemperature related variables seem to account for most of the variation, with window open-time contributing in the fall and interior temperature contributing in the fall.

Modeling Interior Temperature

In this section the effects of door and window openings, and their interactions with other variables, on interior temperature are discussed. Occupants both respond to and determine interior temperature. They control interior temperature by manipulating the windows, doors, and thermostat. Interior temperature is also affected by exterior temperature and the duration of operation of space conditioning appliances (in this case, furnace run-time).

Linear regression analyses were performed using interior temperature as the dependent variable and various combinations of independent variables. The model that explained the greatest amount of variation in the dependent variable utilized all of the independent variables. Thus the independent variables in this analysis are: exterior temperature, thermostat setting, furnace run-time, door open-time and window open-time.

Table XI shows the R^2 values for this equation for each family by season. The model generally performed well in the winter (73%), fall (54%), and spring (40%), and performed moderately well in summer. Applied to the data set as a whole (all families, all days), the model performed less well, with an R^2 of .2962. Performance also varied considerably among families.

Table XII details the explained variance attributable to each independent variable by season. During the winter, when the model worked best (and the season which is most relevant from an energy consumption standpoint), the model accounted for 73% of the variance in interior temperature. However thermostat setting accounted for the great majority of the explained variation, with exterior temperature accounting for nearly all the rest. Door and window openings accounted for 3% of the variance. Ventilation behavior would appear to be not very important in determining winter interior temperature, and the variables improve the model only slightly.

In spring, the model accounted for 40% of the variation, with exterior temerature and furnace run-times the dominant variables. Window and door openings accounted for 14% of the explained variance, and their inclusion in the equation helps to improve its effectiveness. Since a significant amount of space heating takes place in Michigan during the spring, window and door openings are likely to have their biggest impact on energy consumption during this season.

In summer, the model accounts for only 33% of the variation. Again exterior temperature accounts for the largest share of explained variance, but it is in this season that window and doors have their biggest effect on interior temperature. Yet, since none of these houses used air-conditioners, ventilation behaviors probably had their smallest effect on energy consumption.

During the fall, the model's effectiveness is substantial, accounting for 54% of the variance. Exterior temperature and thermostat setting jointly account for over 90% of the variance, with windows accounting for 6% and doors and furnace having little effect.

In general, the model accounted for 30% of the variation in interior temperature. Exterior temperature is the dominant term in the equation, with window and door openings accounting for 14% of the explained variation. The model's effectiveness is enhanced by the inclusion of door and window openings, and the relative importance of these variables increases as the explanatory power of the model decreases in warmer weather. Door and window openings, then, do affect interior temperature although their importance is minor when compared with the effects of exterior temperature and thermostat setting (and spring furnace run-time). The relative importance of door and window openings to the model during the winter, and by implication to space heating energy consumption, is very small.

SUMMARY

Energy and health concerns have identified the need to better understand the effects of ventilation in residences. To date, much work in this area has focused on air infiltration rates as an unintentional effect of building structures. The competing assumptions that the contribution of occupant ventilation behaviors to total winter ventilation are minor, and that occupant behaviors (including window and door use) account for significant variation in energy consumption indicate that further study of the nature and effects of ventilation behaviors is warranted.

This paper discussed electronically monitored door and window openings in a small sample of Michigan households. In addition to door and window openings, thermostat setting, exterior and interior temperatures, and furnace run-time were measured. The Michigan climate provided an opportunity to study well-defined seasonal variation in ventilation.

Window open-time was found to vary by 8 to 1 between different families, while door openings varied by a factor of 4 to 1. Door and window openings were longer in warm weather than in winter. Window open-time exceeded door open-time only in the summer. Thus, during the heating season door openings may affect space heating more than do window openings. While winter window and door use is modest, it is nontrivial since windows are open 2.7% of the time and doors are open 6% of the time.

While earlier studies of window openings have indicated that window use is a function of exterior temperature, this sample indicates that window and door use in the winter is unrelated to temperature and heating variables and is probably related to other factors. It is likely that in locations with well-defined seasons, window and door use is triggered by exterior temperature thresholds and does not vary linearly with exterior temperature.

Coincidental furnace run-time and ventilation behaviors were measured. Furnace use occurred in 6% of the hours that also exhibited window openings, implying that occupant management of windows is fairly good. Window openings occur during 2.6% of the hours exhibiting furnace use. Indications that window openings contribute little to heating energy consumption. Door open-time decreased significantly during hours containng furnace use, but still averaged 17 minutes per hour open-time in those hours when door and furnace use overlapped.

Linear regression using temperature and space heating related independent variables was used to model window and door openings and to model the effects of ventilation behavior on interior temperature. The effectiveness of these models were seasonally variable, as were the relative weights of the independent variables in each equation. The equation explaining window open-time was ineffective in the winter, but accounted for 30% of window use variation overall. Thermostat setting accounted for the most variation in window openings, followed closely by exterior temperature. The door open-time model accounted for 33% of overall door use variation. Exterior temperature accounted for the most variation in door opening, although the effects of thermostat are very important during the spring. Thermostat setting had the greatest effect during the winter on interior temperature, however exterior temperature accounted for more variation during the other seasons. Ventilation behaviors accounted for 22% of the variation in summer interior temperatures and only 3% of the variation during the winter.

Bearing in mind the small size of the sample, this analysis makes the following general conclusions: Variations in ventilation behaviors are significant such that the rate of air movement through houses (and its effects on energy consumption and occupant health) will change seasonally. Door and window opening behaviors are sufficiently different from each other that they reflect different occupant functions and management strategies, and these functions change during different seasons. Unlike in milder climates, ventilation behaviors in locations with significant seasonal changes, cannot be understood solely as a function of exterior temperature.

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FOOTNOTES

1. This research is part of the MSU Family Energy Project in the Institute for Family and Child Study, College of Human Ecology. This work is supported by the Michigan Agricultural Experiment Station (Project 3152). The data were collected as part of work supported by grants from the National Science Foundation (BNS 82-10088, Kempton and Keith Principal Investigators) and the Kellogg Biological Station Small Farms Project. This paper is Michigan Agricultural Experiment Station Journal Article No. 12041.

2. This family reported that they rarely used windows for ventilation. We placed a sensor only on the one window they did claim to use. Equipment filures in this household also severely limited the amount of reliable window data. Even when we were sure that the window sensor was operative we recorded no window openings at all.

3. Since window openings usually lasted many hours at a time, minutes open per hour (for hours containing any window open-time) did not vary much between families, little would have been gained performing a similar calculation with window open-time.

4. Adjusted R^2 values are compensated for the degrees of freedom in the equation and can be compared to values produced by other equations.

Table I. Number of days in total sample and for reliable ventilation data, by family.

	Number of Days of Data			
Family	Total	Window	Door	Occupants
1	507	251	507	4
2	396	201	396	2
3	512	512	512	3
4	372	372	372	3-4
5	579	579	271	5-7
6	364	364	364	4
7A	164	164	164	4
7B	189	189	189	4

Table II. Mean hourly statistics for each variable, by family (based on daily summaries). Standard deviations are wieghted by group. * Window data for this family unreliable.

Family	Interior Temp.	Thermostat Setting	Door Open Min./Hour	Window Open Min./Hour	Furnace Run Min./Hour	Exterior Temp.
1	73.0	65.3	12.1	21.9	10.7	43.7
2	70.2	63.4	16.4	0.0*	4.5	48.6
3	72.2	67.2	7.5	15.4	15.9	50.8
4	67.2	60.5	18.2	22.7	5.0	46.3
5	77.1	64.2	5.3	8.6	8.0	46.5
6	72.0	63.7	20.4	16.0	10.1	49.4
7A	70.5	68.3	9.4	2.6	5.4	43.9
7B	68.7	66.4	13.8	4.0	4.0	44.3
All	72.0	64.5	12.8	12.3	9.0	47.0
Standard Deviations	4.6	8.4	15.5	23.4	10.4	

Table III. Mean Hourly Statistics for All Families, by Season

Season	Interior Temp.	Thermostat Setting	Exterior Temp.	Window Open Min./Hour	Door Open Min./Hour	Furnace Run Min./Hour
Winter	70.3	70.0	29.4	1.6	3.6	18.1
Spring	72.3	63.8	53.1	13.9	16.2	4.9
Summer	75.8	54.7	68.6	33.1	28.8	0.1
Fall	70.8	64.4	51.2	7.26	10.3	6.2

Table IV. Correlation matrix for all families, all seasons. Pearson's r, Number of cases, and Student's t.

	EXTERIOR	THERMO.	INTERIOR	WINDOW	DOOR	FURNACE
EXTERIOR TEMP.	—	-0.6329 3083 -45.369	0.4730 3083 29.795	0.5084 2632 30.280	0.5778 2775 37.280	-0.7266 3083 -6.626
THERMO. SETTING		—	-0.1981 3083 -11.218	-0.5025 2632 -29.804	-0.4954 2775 -30.035	0.5959 3083 41.190
INTERIOR TEMP			—	0.2514 2632 13.320	0.3392 2775 18.990	-0.2034 3083 -11.530
WINDOW OPEN TIME				—	0.3794 2324 19.757	-0.3923 2632 -21.87
DOOR OPEN TIME					—	-0.4697 2775 -28.016
FURNACE RUN TIME						—

Table V. Correlation Matrices for all families, summer and winter. Pearson's r, number of cases, and Student's t statistic.

	EXTERIOR	THERMO.	INTERIOR	WINDOW	DOOR	FURNACE
EXTERIOR	—	-0.0373 1110 -1.244	0.1205 1110 4.041	-0.0503 916 -1.522	0.0675 1047 2.186	-0.2943 1110 -10.250
THERMO	-0.0012687 536 -0.029	—	0.8523 1110 54.229	-0.0458 916 -1.385	0.00853 1047 0.287	0.3024 1110 10.561
INTERIOR	0.5186 536 14.015	-0.3479 536 -8.576	—	-0.0161 916 -0.487	0.0329 1047 1.063	0.1687 1110 5.698
WINDOW	0.5594 490 14.907	-0.1477 490 -3.298	0.2968 490 6.866		0.0383 853 1.117	-0.0687 916 -2.081
DOOR	0.0167 444 0.352	-0.2413 444 -5.227	0.2034 444 4.368	-.0016799 398 -0.033	—	-0.0697 1047 -2.258
FURNACE	-0.0744 536 -1.725	0.1685 536 3.951	-0.1753 536 -4.114	-0.1257 490 -2.799	-0.0967 444 2.042	—

WINTER

SUMMER

Table VI. Correlation Matrices for all families, spring and fall. Pearson's r, number of cases and Student's t statistic.

	EXTERIOR	THERMO.	INTERIOR	WINDOW	DOOR	FURNACE
EXTERIOR	—	-0.5670 1074 -22.537	0.4515 1074 16.569	0.4668 890 15.728	0.6066 982 23.888	-0.7154 1074 -33.525
THERMO	-0.2513 363 -7.128	—	-0.1910 1074 -6.371	-0.4204 890 2.495	-0.3171 982 8.952	0.5698 1074 -3.080
INTERIOR	0.3714 363 7.600	0.2083 363 4.046	—	0.0834 890 2.495	0.2749 982 8.952	-0.0937 1074 -3.080
WINDOW	0.1799 336 3.342	-0.5318 336 -11.477	-0.2591 336 -4.902	—	0.3733 798 11.354	-0.3820 890 -12.316
DOOR	0.1888 302 3.330	-0.2985 302 -5.417	-0.0645 302 -1.120	0.3270 275 5.178	—	-0.4414 982 -15.399
FURNACE	-0.4427 363 -9.381	0.4384 363 12.138	-0.0115 363 -0.218	-0.3100 330 -5.958	-0.2732 302 -4.920	—

SPRING

FALL

Table VII. Coincidental ventilation behavior and furnace on-time Window/Furnace is the percent of total window open hours that contain furnace run-time. Furnace/Window is % of total furnace run-time hours that contain window open-time. * = Insufficient Data

Family #	Window/Furnace %	Furnace/Window %	Door Open (mean)	Door Open W/Furnace
1	6	2	41	38
2	*	*	16	17
3	1	1	37	22
4	1	2	13	27
5	5	2	44	17
6	9	4	52	40
7A	0	0	35	17
7B	75	13	22	19
All	6	3	34	26

Table VIII. R^2 values of window and door model equations, by house and season. Window equation independent variables are exterior temp., interior temp., thermostat setting, and door open-time. Door equation independent variables substitute window opening for door opening. * = Insufficient data.

	Window Equation				Door Equation			
Family	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
1	-.0012	.4209	.1539	*	.0441	4581	.7067	1438
2	*	*	*	*	-.0399	.6280	.0767	4095
3	0032	.7117	.4762	.0154	.0170	.5445	1840	.2504
4	-.0032	3887	.3301	.6068	.0594	.3586	.0349	.2449
5	0788	.0302	-.1456	.1632	.1213	2789	.0973	*
6	-.0072	8129	.6125	.1442	.0623	.5538	.2465	.2697
7A	-.0164	-.0064	.3735	.1826	.2088	.5713	.0159	.3434
7B	.0665	.1408	.0313	*	.1058	.5335	.0624	*
All	.0046	.2710	.3223	.4681	-.0010	.3612	.0724	.1103

Table IX. Proportions of explained variance in window open-time accounted for by independent variables in linear regression. * Insignificant @ .05

Season	Adjusted R^2	% Exterior	% Interior	% Door	% Thermostat
Winter	-.0013*	---	---	---	---
Spring	.2710	37	11	21	31
Summer	.3223	71	13	1	16
Fall	.4681	4	10	15	72
All	.3034	34	10	15	41

Table X. Proportions of explained variance in door open-time accounted for by independent variables in linear regression. * Insignificant @ .05

Season	Adjusted R^2	% Exterior	% Interior	% Window	% Thermostat
Winter	-.0009*	---	---	---	---
Spring	3612	62	15	14	8
Summer	.0724	20	36	2	42
Fall	.1103	17	5	52	26
All	.3346	45	28	13	14

Table XI. Adjusted R^2 values of interior temperature model. Independent variables are: Exterior temp., thermostat setting, window and door open-times, and furnace run-time. * Insufficient data.

Family	Winter	Spring	Summer	Fall
1	.8854	.5332	.6262	.7013
2	.9449	.7851	.1785	.5386
3	.3837	.6488	.8761	.3213
4	.7675	.7411	.9041	.7893
5	.2363	.5011	.3824	.5255
6	.5856	.6574	.5063	.2967
7A	.9739	.4795	.8530	.4343
7B	.3408	.7528	.7188	*
All	.7359	.4047	.3262	.5430

Table XII. Proportions of explained variance in interior temperature accounted for by independent variables in linear regression.

SEASON	ADJUSTED R^2	% EXTERIOR	% WINDOW	% DOOR	% FURNACE	% THERMOSTAT
Winter	.7359	11	2	1	7	78
Spring	.4047	58	5	9	27	1
Summer	.3262	52	11	11	11	15
Fall	.5430	44	6	1	2	48
All	.2962	51	5	9	18	17