Title

Testing of peak demand limiting using thermal mass at a small commercial building

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TESTING OF PEAK DEMAND-LIMITING USING THERMAL MASS AT A SMALL COMMERCIAL BUILDING

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EXECUTIVE SUMMARY

This report presents results from field testing and comfort surveys designed to evaluate peak demand-limiting strategies that utilize both precooling and adjustments of zone cooling setpoints. The testing was performed over a two-week period at a small bank building in Palm Desert, California. During the first week test, three kinds of control strategies were considered:

1) conventional night setup control as a baseline case,
2) a simple linear-rise demand-limiting strategy that involved precooling during the morning and linear setpoint adjustments during an afternoon demand-limiting period, and
3) a simple step-up demand-limiting strategy that included precooling in the morning and resetting of setpoint during the demand-limiting period.

During the second week of testing, a demand-limiting strategy was tested for four days with setpoint trajectories determined using a weighted-averaging method developed at Purdue University. Precooling of the building was performed at 70ºF setpoint from 6am to 12pm and setpoints during the on-peak period from 12pm to 6pm were modulated from 70 to 78ºF following a trajectory that attempted to minimize peak cooling load. (The measured temperature at the polling station was a minimum of 1.5 degrees F above the thermostat setpoint (see figures 24 to 29 in appendix). The baseline was conventional night-setup control with a 72ºF cooling setpoint temperature during the occupied period. The demand-limiting tests resulted in greater than 30% reduction of peak air conditioner power on average for the four tested days which accounted for 0.76W/ft^2 peak savings.

The comfort survey revealed that the response of occupants was highly variable at any given indoor temperature. Statistical analysis of all the data collected, including baseline days and test days, indicated a significant probability that a given occupant will vote that the temperature is ‘cool’ at the low setpoint temperature of 70 degrees (between 30 and 50 percent), and ‘warm’ at the upper setpoint of 78 degrees (between 37 and 52 percent) (figure 21). However, only half of these votes are at the level where the

respondent says it ‘bothers’ them. The probability of a given occupant being bothered by the ‘cool’ temperature at the low setpoint is estimated to be 17 percent and the probability of a given occupant being bothered by the ‘warm’ temperature at at the upper setpoint is estimated to be 23 percent. (figure 22). If we assume the neutral temperature to be between 74 and 75 degrees F, the probability of dissatisfaction (both ‘Too warm! It bothers me’ and ‘Too cool! It bothers me’) is estimated to be 20 percent.

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INTRODUCTION

Background

There have been a few simulated and experimental studies that have demonstrated potential for reducing peak cooling demand using building thermal mass through control of zone temperatures for small commercial buildings. Lee and Braun (2006a) developed a model-based demand-limiting method that relies on a detailed inverse model. The method was trained using data from the Energy Resource Station building that houses the Iowa Energy Center and validated experimentally by Lee and Braun (2006b). The test results showed 30% reductions in peak cooling loads with setpoint adjustments from 70 to 76°F for a 5-hour demand-limiting. These results are consistent with simulation results that were determined for this facility. Lee and Braun (2006c,d) also developed a more simplified method, which is termed the weighted-averaging method (WA method) for determining demand-limiting setpoint trajectories using short-term measurements. The method doesn’t require a building model and weather data but only requires cooling load or associated power data. The method was evaluated for different buildings using trained inverse building models and simulations. Simulation results showed that the method is effective for peak load reduction compared to optimal control assuming perfect knowledge of building thermal response and perfect prediction of weather conditions.

Objectives

The goal of the current project was to perform field testing to demonstrate peak cooling demand reduction for a small commercial building using a demand-limiting control strategy based on the weighted-averaging method of Lee and Braun (2006c) and to evaluate comfort of occupants. The demand-limiting control strategy in this study involves precooling a building in the morning at a lower bound of comfort, i.e. 70ºF and then warming up the building by modulating the cooling setpoint temperatures up to an upper bound of comfort temperature, i.e. 78ºF.

Accomplishments

The resulting demand-limiting strategy was tested for four days in October with clear sky conditions and a maximum outdoor temperature between 80 and 85ºF. The baseline was conventional night-setup control with a 72ºF cooling setpoint temperature during the occupied period from 6am to 7pm. The demand-limiting control was performed with precooling at 70ºF from 6am to 12pm and setpoint adjustment up to 78ºF during an on-peak period from 12pm to 6pm. The demand-limiting setpoint trajectory was determined with the WA method developed by Lee and Braun (2006c). The test results showed a peak air conditioning power reduction of more than 30% or 0.76W/ft^2. The comfort survey showed that the range of precooling and setpoint setups in this test did not affect the customers significantly, regardless of indoor-outdoor temperature differences. The bank employees are more likely to be the limiting factor, since their exposure is far longer. Setpoint limits for employees under precooling conditions have been studied in a large commercial building located in Visalia (Xu, Brown 2007).

DESCRIPTION OF TEST FACILITY AND PROCEDURES

Test Building

The selection criteria for the small commercial building site included:

- a building representative of common construction design of buildings of this size
- wire-to-wire compatible retrofit for new page-able thermostats
- a building occupancy typical of small commercial facilities in this size range
- located in a hot climate

The building selected was a small single tenant bank located in Palm Desert, California.

Figure 1. Building Picture / Satellite Photo

The interior of the building was representative of a traditionally designed bank, including a typical teller arrangement and side areas for account representatives:

Figure 2. Teller Stations / Account Represenatives

Other areas of the bank for employees and other offices were typical:

Figure 3. Lunch Room / Copy Room

The building construction is summarized as follows:

Building Geometry and Construction

	Value/Description
Total floor area [ft2]	12,000
Number of stories	One
Percentage of exterior walls that are windows [%]	36%
Description of exterior wall materials and thicknesses	Stucco over wood framing. 6” thick
Description of windows	Single pane tinted
Description of floor construction and treatments (e.g., 4” concrete, carpeted)	4” concrete with ceramic tile and carpet
Description of internal walls and other thermal mass	5/8 drywall over wood framing

Building Schedules and Internal Gain

	Value/Description
Start of Occupancy	8:00 A.M.
End of Occupancy	7:00 P.M.
Start of On-Peak Period	12:00 PM
End of On-Peak Period	6:00PM
Lighting [W/ft2]	1.25
Number of computers	30
Number of people	25

The metering information for the building is as follows:

Meter	**Tariff**	**Phase**	**Voltage**	**Max. kW**
1	GS-2	3	208	31
2	GS-1	3	208	11
3	GS-1	3	208	2
4	GS-1	3	208	10
5	GS-1	3	208	17

The building includes multiple meters since the original construction included the option for multiple tenants. The meters in this case, however, were all in the name of the bank.

Air Conditioning Equipment

The HVAC equipment for this facility is listed in the following table.

Unit	Type	Mfg.	Model #	Serial#
1	PU - AC	York	D7CG048N0GO35A	NGFM082738
2	PU - AC	York	D7CG048N06025A	NGFM076173
3	PU - AC	York	D7CG060N07925A	NEGM064006
4	PU - AC	York	D7CG060N07925A	NDGM04493
5	PU - AC	York	DCG060N07925A	NDGM044492
6	PU - AC	York	D7CG048N06025A	NCGM031022
7	PU - AC	York	D7CG048N06025A	NCGM029934
8	PU - AC	York	D7CG060N07925A	NCGM029436
9	PU - AC	York	D7CG060N07925A	NCGM029435
10	PU - AC	York	D7CG060N07925A	NBGM023232
11/12	PU – AC	Data Aire	DRCU-0334	99-0346-A

Two of the units were not monitored since the office space they served was unoccupied. Additionally, two small data center units were also not monitored since they served a data processing room which was not part of the occupied space.

Data Measurement

The packaged air conditioning systems' electric load was monitored with data recorders installed specifically for the testing. Air conditioning for the occupied rooms in the building were traced to eight air conditioning units. The circuits for the eight air conditioning units were traced to electric panels located in three different rooms.

Three Synergistic Meter/Recorders (model C-180) were installed at the site, to monitor and record electric demand of the air conditioning units. The Synergistic loggers have 16 hardware input channels. Each channel measures kW load on a single phase. Several hardware channels are combined with soft settings to measure three phase loads. The meters measure true rms power. Split-core current transducers (CT) with 30 Amp ratings were used for individual air conditioning units, and 100 Amp rated CTs were used on a pair of air conditioning units. The data loggers were set to record average kW demand at 15-minute intervals. Clocks on the loggers were synchronized to the NIST (National Institute of Standards and Technology) clock available on the web.

The data loggers have enough memory to store more than a month of data before a site visit was needed to download data. The air conditioning power was measured separately using hand-held instruments, to validate the logger data. Total air conditioning power was determined during post processing as the sum of the individual recorded data channels.

Setpoint Schedule

The testing was carried out over two weeks. The first week of testing was performed from October 9 to 13 for five days to obtain baseline test data and preliminary simple precooling test data. The baseline control is conventional night-setup and the preliminary simple precooling tests included 'linear-rise (LR)" and 'step-up (SU)' strategies with precooling in the morning as shown in Figure 4. The second week of testing was performed from October 23 to 27 for five days with the baseline control and demand-limiting (DL) control strategies. Demand-limiting setpoint trajectories were determined using the WA method (Lee and Braun, 2006c). The weighting factor is determined by minimizing the peak of the weighted-averaged cooling loads determined for two different test tests. The weighting factor is determined by minimizing the following objective function

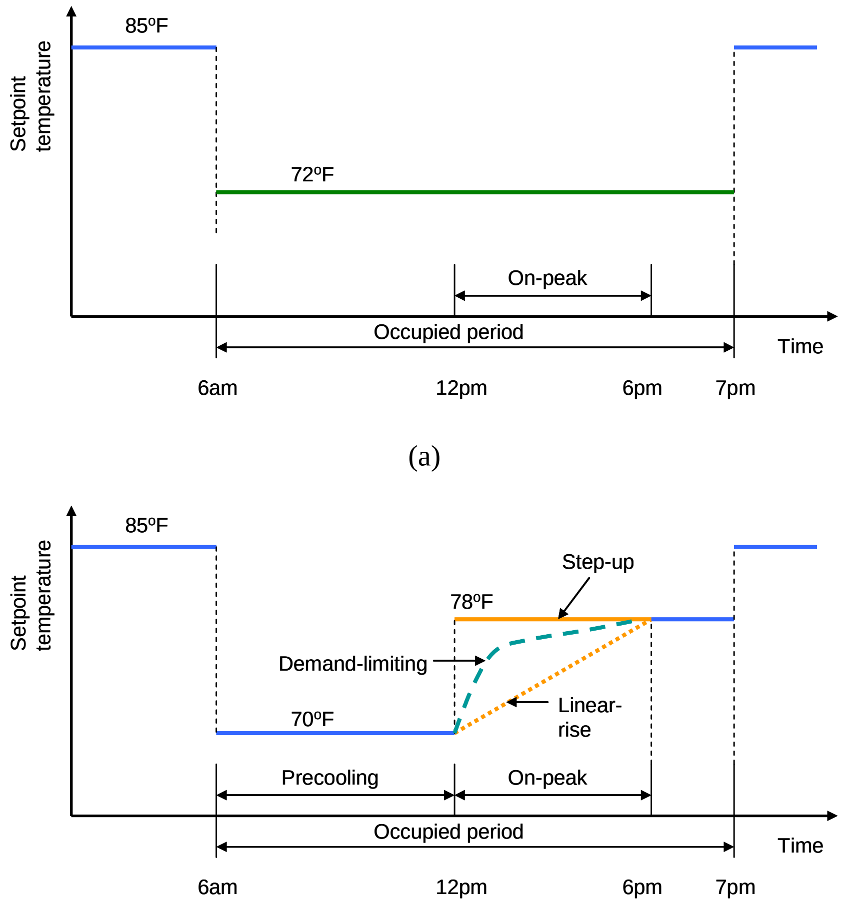
$$J = \max_{w^*}\left[w\dot{Q}_{1,k} + (1-w)\dot{Q}_{2,k} \right] = \max_{w^*}\left[\dot{Q}_{w,k} \right] \text{ for the demand-limiting period} \qquad (1)$$

with respect to the weighting factor *w*, where $\dot{Q}_{1,k}$ is the cooling load for time interval *k* under control 1, $\dot{Q}_{2,k}$ is the cooling load at time k under control 2, and $\dot{Q}_{w,k}$ is the weighted-averaged cooling load at time *k*.

The WA method employs the assumption that the cooling load at any time is a linear function of the zone temperature. With this assumption, the zone temperature trajectory that minimizes the peak load is

$$T_{z,w,k} = w^* T_{z,1,k} + (1-w^*) T_{z,2,k} \text{ for the demand-limiting period} \qquad (2)$$

where $T_{z,1,k}$ is the zone setpoint temperature for time interval k with control 1, $T_{z,2,k}$ is the zone setpoint temperature for control 2 at time *k*, $T_{z,w,k}$ is the optimally weighted-averaged zone setpoint temperature at time *k*, and w^* is the optimal weighting factor determined by minimizing the cost function in equation (1).



(a)

(b)

Figure 4. Setpoint control strategies: (a) baseline night-setup (NS) control and (b) demand-limiting (DL) control strategies

The setpoint trajectory of equation (2) that is obtained from the weighted-averaging is then adjusted using the following equation (Lee and Braun, 2006c).

$$T_{z,dl,k} = T_{z,w,k} + \Delta T_{adj,k} \tag{3}$$

$$\Delta T_{adj,k} = \frac{\dot{Q}_{w,k} - \dot{Q}_{w,avg}}{\max\left|\dot{Q}_{w,k} - \dot{Q}_{w,avg}\right|} T_{adj,\max} \tag{4}$$

where $\dot{Q}_{w,k}$ is the weighted-averaged cooling load using $\dot{Q}_{1,k}$ and $\dot{Q}_{2,k}$ at time k, $T_{adj,\max}$ is the maximum allowable adjustment temperature for a given hour (1.0°F in this testing), and $\dot{Q}_{w,avg}$ is the average of the weighted-averaged cooling load $\dot{Q}_{w,k}$ over the demand-limiting period which is assumed to be the target peak cooling load.

The occupied cooling period was from 6am in the morning to 7pm in the evening. The on-peak period or demand-limiting period was from 12 pm to 6pm for the tests. For the unoccupied period from 7pm to 6am, the setpoint temperature was setup at 85ºF for all control strategies.

For the other periods except the two week test period during the summer, the night-setup control was employed for building cooling.

Week 1 testing:

Table 1 shows the setpoint schedule used for the first week of testing. October 9, 10, and 13 were controlled using night-setup (NS) control for the baseline and October 11 and 12 were for used for obtaining preliminary test data to provide input data for the WA method to determine demand-limiting setpoints.

Week 2 testing:

Table 2 shows the setpoint schedule applied for the second week of testing that includes one day with NS control and four days with DL control. For the first two days of DL control, October 24 and 25, the setpoint trajectory from the weighted-averaging step (equation 2) in the WA method was used whereas the adjusted setpoint trajectory (equations 3 and 4) was employed for the last two days of October 26 and 27. The setpoint trajectories determined with the WA method could not be precisely implemented because the thermostat only allows integer numbers for setpoint values and the time interval between setpoint changes was restricted to 15 minutes. Therefore, the trajectories implemented on October 24 and 25 bound the trajectory determined with equation 2. Similarly, the trajectories implemented on October 26 and 27 bound the trajectory determined with equations 3 and 4. Figure 5 shows the demand-limiting setpoint trajectories with and without adjustment of the setpoint trajectory in the WA method.

Table 1: Actual cooling setpoint schedules during the first week for baseline testing

	1st day (10/9)	**2nd day (10/10)**	**3rd day (10/11)**	**4th day (10/12)**	**5th day (10/13)**
Setting 1 (Time/Temp)	8:00 AM 72°F	8:00 AM 72°F	6:00 AM 70°F	6:00 AM 70°F	6:00 AM 72°F
Setting 2 (Time/Temp)	7:00 PM 85°F	7:00 PM 85°F	12:00 PM 71°F	12:00 PM 78°F	7:00 PM 85°F
Setting 3 (Time/Temp)			12:45 PM 72°F	7:00 PM 85°F	
Setting 4 (Time/Temp)			1:45 PM 73°F		
Setting 5 (Time/Temp)			2:30 PM 74°F		
Setting 6 (Time/Temp)			3:30 PM 75°F		
Setting 7 (Time/Temp)			4:15 PM 76°F		
Setting 8 (Time/Temp)			5:00 PM 77°F		
Setting 9 (Time/Temp)			5:30 PM 78°F		

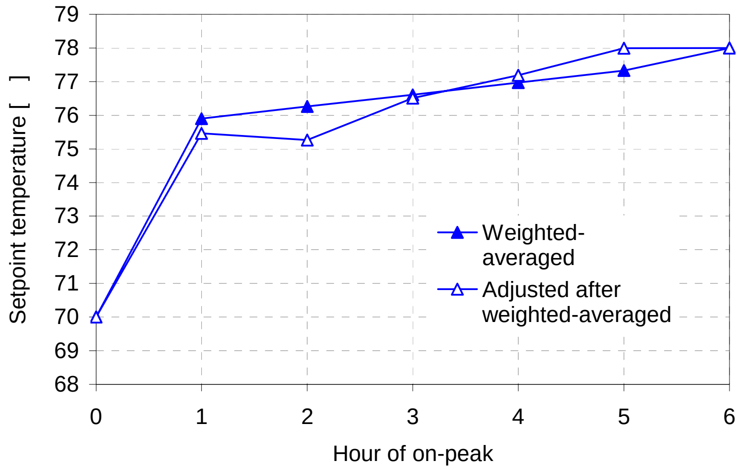


Figure 5. Demand-limiting setpoint trajectories determined by WA method.

Table 2: Actual cooling setpoint schedules during
the second week for demand-limiting test

	1st day (10/23)	**2nd day (10/24)**	**3rd day (10/25)**	**4th day (10/26)**	**5th day (10/27)**
Setting 1 (Time/Temp)	º6:00 AM 72ºF	6:00 AM 70ºF	6:00 AM 70ºF	6:00 AM 70ºF	6:00 AM 70ºF
Setting 2 (Time/Temp)	7:00 PM 85ºF	12:00 PM 71ºF	12:00 PM 71ºF	12:00 PM 71ºF	12:00 PM 71ºF
Setting 3 (Time/Temp)		12:15 PM 72ºF	No change	12:15 PM 72ºF	No change
Setting 4 (Time/Temp)		No change	12:15 PM 73ºF	continued	12:15 PM 73ºF
Setting 5 (Time/Temp)		12:30 PM 74ºF	12:30 PM 74ºF	12:30 PM 74ºF	12:30 PM 74ºF
Setting 6 (Time/Temp)		12:45 PM 75ºF	No change	12:45 PM 75ºF	12:45 PM 75ºF
Setting 7 (Time/Temp)		1:00 PM 76ºF	12:45 PM 76ºF	2:00 PM 76ºF	2:00 PM 76ºF
Setting 8 (Time/Temp)		1:15 PM 77ºF	1:15 PM 77ºF	2:45 PM 77ºF	2:45 PM 77ºF
Setting 9 (Time/Temp)		4:00 PM 78ºF	4:00 PM 78ºF	3:45 PM 78ºF	3:45 PM 78ºF
Setting 10 (Time/Temp)		7:00 PM 85ºF	7:00 PM 85ºF	7:00 PM 85ºF	7:00 PM 85ºF

Administration of Comfort Survey

Owners of retail spaces want to know how demand shifting/shedding strategies may affect customers as well as employees. To study this, CBE developed stand-alone polling stations for surveying customers in retail spaces (Figure 7), since internet access is usually not easily available in such places. This device asks about sensation/comfort using a 5-point scale.

Dear Customer,
We are testing a new heating and cooling system that could reduce the cost of California's electricity. Please let us know what you think of the temperature in this building.

Please choose one of the following:

Too warm! it bothers me
Warm, but it does not bother me
Just right

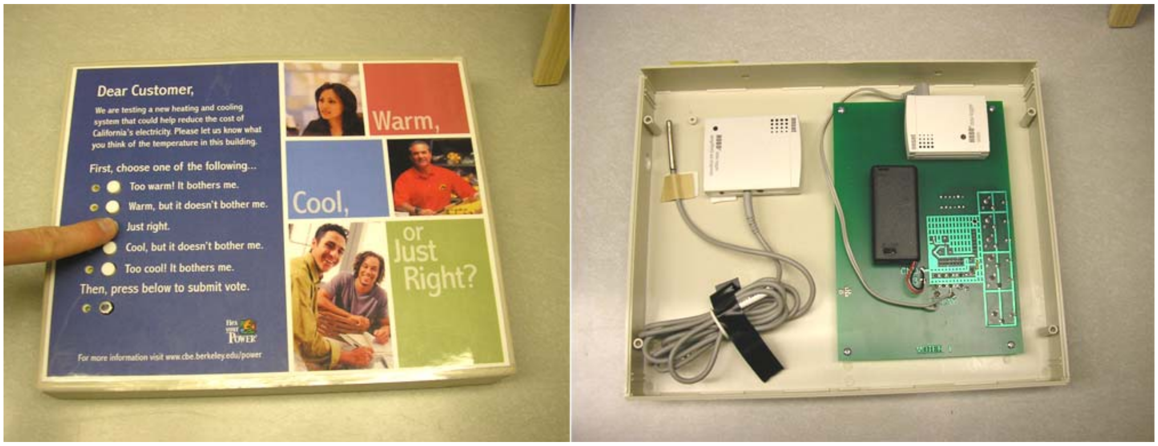
Cool, but it does not bother me
Too Cool! it bothers me

In the Palm Desert bank branch, permission was obtained from the bank manager to mount a single device at eye-level on one of the bank's display boards. The display board was positioned adjacent to the counter where customers queue while waiting to see a bank teller (Figure 6). Both customers and employees were allowed to use the polling station.

Figure 6. Location of stand-alone polling station within Palm Desert bank branch

Data Collection

The polling station contains a Hobo temperature/RH data logger programmed to log temperature/RH readings at the polling station every three minutes. These are synchronized with the sensation votes which are recorded with a Hobo state logger. Both loggers are capable of logging data for one month before their memory capacity is exceeded.



Dear Customer,

We are testing a new heating and cooling system that could help reduce the cost of California's electricity. Please let us know what you think of the temperature in this building.

First, choose one of the following...

Too warm! It bothers me.

Warm, but it doesn't bother me.

Just right.

Cool, but it doesn't bother me.

Too cool! It bothers me.

Then, press below to submit vote.

For more information visit www.cbe.berkeley.edu/power

Figure 7. Polling station for surveying bank customers

The polling station was placed in the Palm Desert bank branch and activated on 9/15/2006. To accommodate extensions in the testing schedule, the data from the loggers was downloaded on 10/12/2006 and the data loggers were reinitialized. Temperature/RH data was collected from 9/15/2006 to 11/17/2006. Voting data was collected from 9/15/2006 to 9/25/2006 and from 10/12/2006 to 11/17/2006. No votes were logged from 9/26/2006 to 10/11/2006 due to an unforeseen problem with the state logger's batteries.

Both employees and customers were eligible to participate and participation was voluntary. No incentive or instructions (other than those printed on the voting station) were given to the customers or the employees.

TEST AND SURVEY RESULTS

Peak Demand Reduction

During the first week of testing, October 9 was selected as a baseline day, that had comparable outdoor weather conditions as October 11 and 12 when the LR and SU strategies were tested. Measured outdoor temperatures and air conditioning load profiles are compared in Figure 8 and Figure 9, respectively. Outdoor temperature data were available from a local weather station near Palm Desert. A shaded region in Figure 9 indicates the on-peak period from 12pm to 6pm. The morning peak load is dramatic at the beginning of building cooling. The afternoon load shape is also very sensitive to the shape of the zone temperature variation. Neither a LR strategy (10/11) nor a SU strategy (10/12) resulted in very good load shapes from the viewpoint of peak load reduction.

The LR strategy produced high loads at the beginning of the on-peak period and low loads at the end. Conversely, the SU strategy resulted in very little load at the beginning and a peak near the end of the on-peak period. These results are very consistent with results presented by Lee and Braun (2006a) for prototypical small commercial buildings. Peak air conditioning load and peak load savings for these comparable days are compared in Table 3 with maximum outdoor temperatures and average sky cloud covers. Average sky cover data for Palm Desert were available from the National Weather Service.

DL control was tested for four days from October 24 to 27. Three days of October 24, 25, and 27 except October 26 had similar outdoor weather conditions. As the baseline October 17 was selected for evaluating test performance with demand-limiting control for October 26. Measured outdoor temperatures and air conditioner power profiles for those two comparable days are shown in Figure 10 and Figure 11, respectively. Air conditioning load in DL control was significantly reduced during the on-peak period. Peak air conditioner powers and peak power savings are represented for the two days in Table 4 with maximum outdoor temperature and average sky cover. Peak power savings are considerably increased compared with the simple strategies such as LR and SU controls.

To evaluate performance of the DL strategy for three days (10/24, 10/25, and 10/27) during the second week testing, October 19 was selected for the baseline case. Measured outdoor temperature for these four days (10/19 in NS, 10/24, 25, and 27 in DL) are compared in Figure 12. Measured air conditioner power profiles for the four days are compared in Figures 13 to 15. Peak air conditioner power and peak power savings for the four days are represented in Table 5 with maximum outdoor temperatures and average sky covers. Significant cooling load reductions during the on-peak period are shown for the three days with DL control compared to the baseline with NS control. The air conditioning load profiles were not as flat as anticipated by the DL control. One of the major reasons would be the limitation for precision of setpoint temperatures and the resetting time interval. If setpoints could be adjusted more finely, the air conditioner power profiles could be flatter.

Percent peak air conditioner power savings are compared in Figure 16. Demand-limiting control with setpoint trajectories determined with the WA method showed better performance for peak air conditioner power reduction than the simple strategies such as

LR and SU. The average peak air conditioner power reduction for the four test days with DL control was 31.6% as compared with the baseline. The average and maximum of the peak power savings for the four DL test days were 9.1 and 10.1 kW or 0.76 and 0.84W/ft^2.

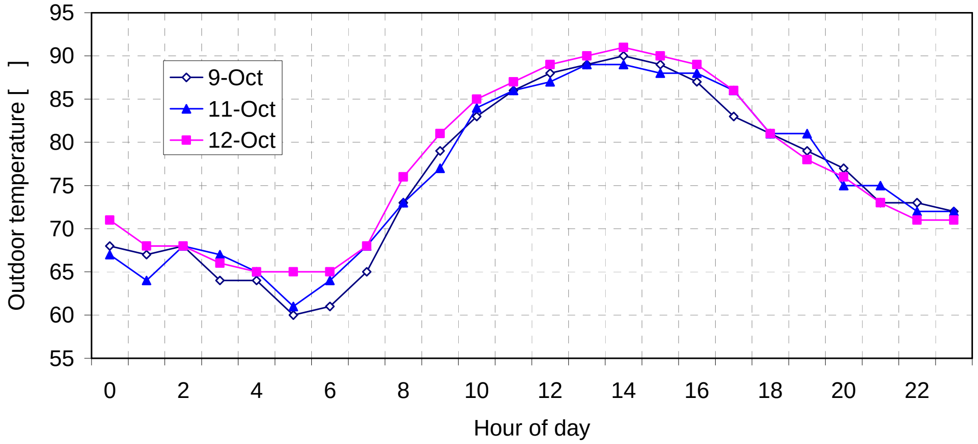


Figure 8. Measured outdoor temperatures for comparable three days of October 9, 11, and 12

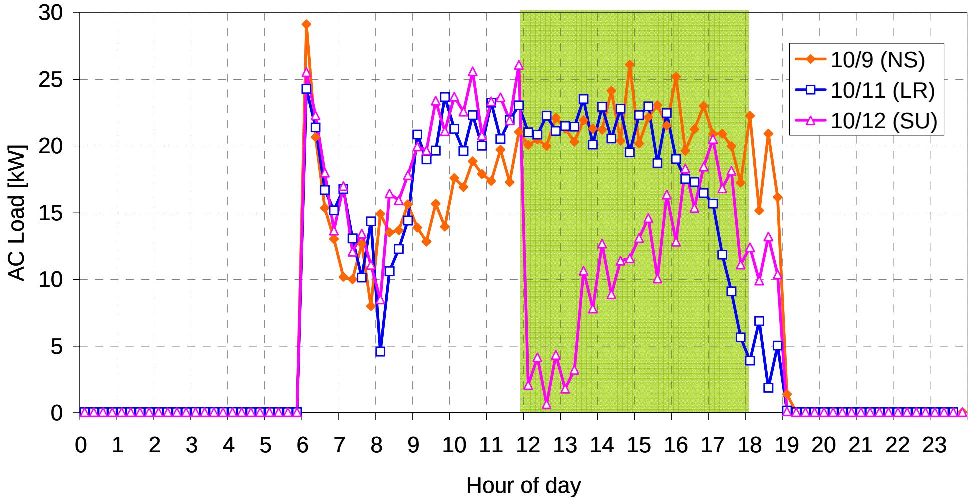


Figure 9. Measured air conditioning powers for comparable three days of October 9, 11, and 12.

Table 3: Peak air conditioning powers for October 9, 11, and 12

Date	$T_{out,max}$ [ºF]	Average sky cover	Control strategy	Peak power [kW]	Power savings [kW]
10/9	90	0	NS	26.10	-
10/11	89	0.1	LR	23.53	2.57
10/12	91	0.1	SU	20.52	5.58

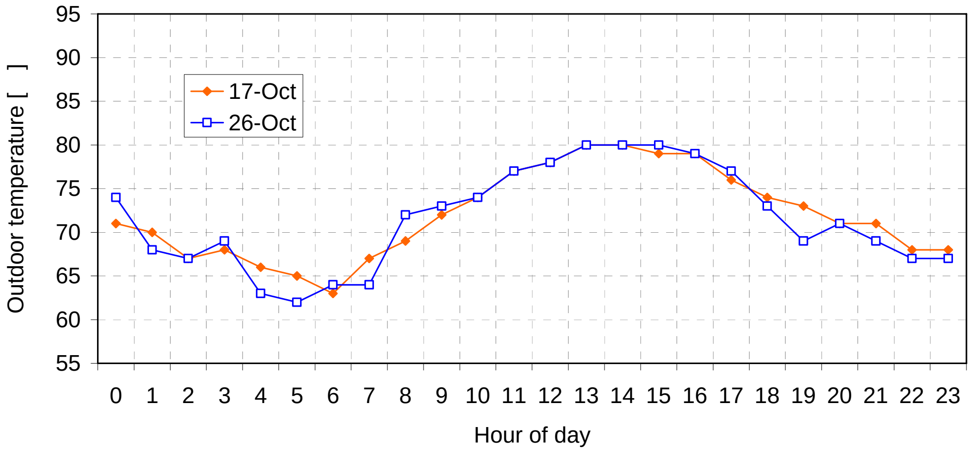


Figure 10. Measured outdoor temperatures for comparable two days of October 17 and 26

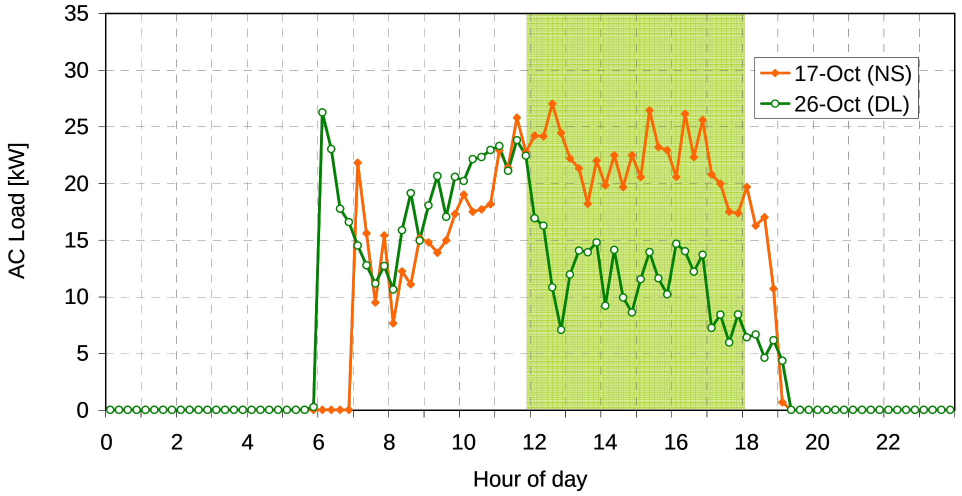


Figure 11. Measured air conditioning powers for comparable two days of October 17 in NS and October 26 in DL control

Table 4: Peak air conditioning powers for October 9, 11, and 12

Date	$T_{out,max}$ [°F]	Average sky cover	Control strategy	Peak power [kW]	Power savings [kW]
10/17	80	0.2	NS	27.04	-
10/26	80	0.0	DL	16.94	10.10

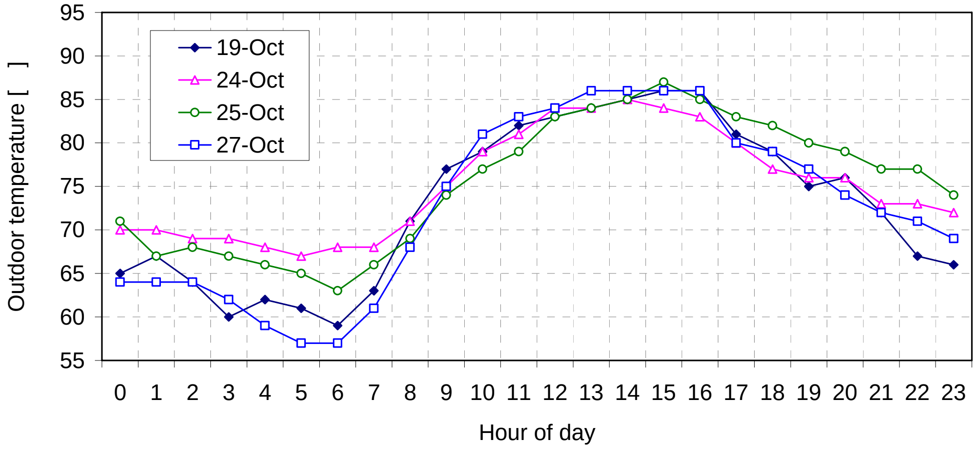


Figure 12. Measured outdoor temperatures for comparable four days of October 19, 24, 25, and 27

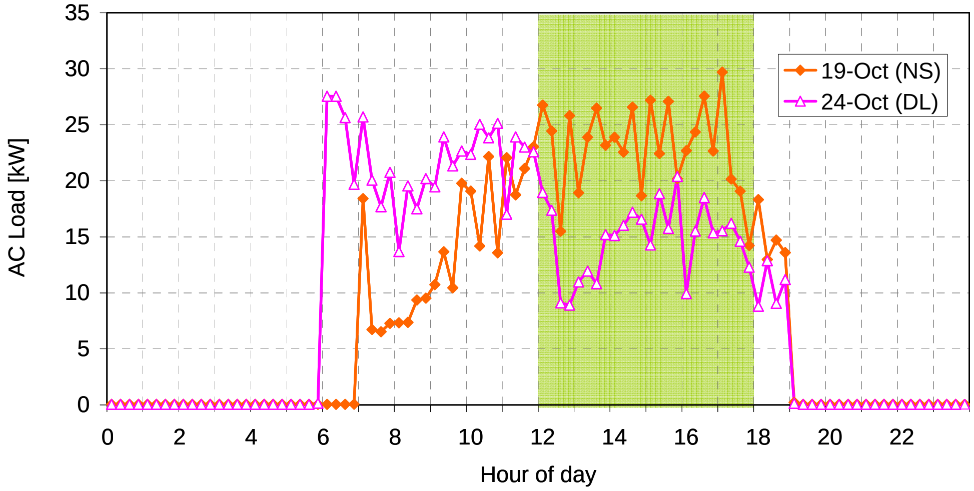


Figure 13. Measured air conditioning powers for comparable two days of October 19 in NS and October 24 in DL control

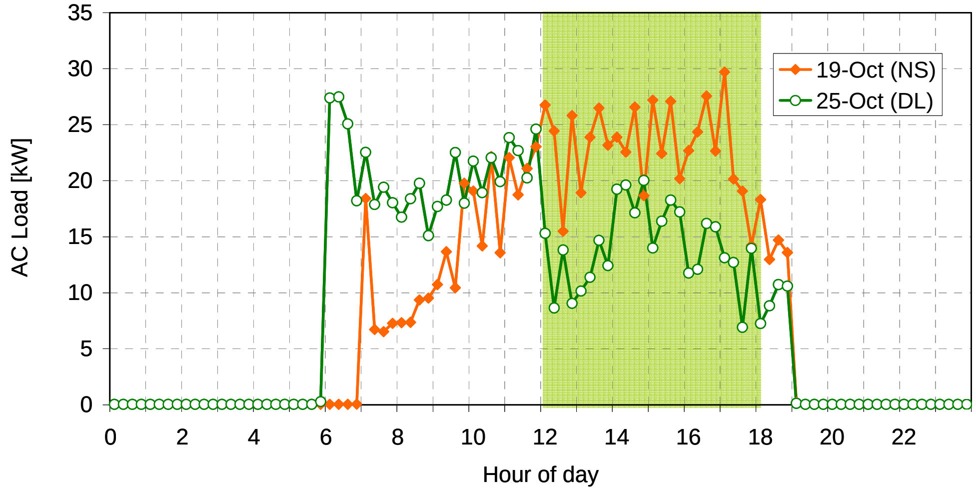


Figure 14. Measured air conditioning powers for comparable two days of October 19 in NS and October 25 in DL control

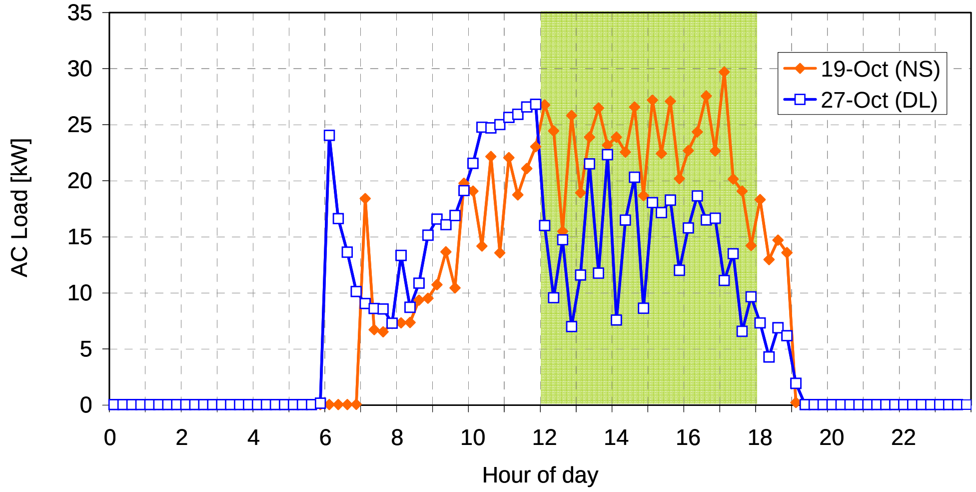


Figure 15. Measured air conditioning powers for comparable two days of October 19 in NS and October 27 in DL control

Table 5: Peak air conditioning powers for October 19, 24, 25, and 27

Date	**$T_{out,max}$ [ºF]**	**Average sky cover**	**Control strategy**	**Peak power [kW]**	**Power savings [kW]**
10/19	85	0.0	NS	29.70	-
10/24	85	0.2	DL	20.38	9.32
10/25	86	0.2	DL	20.03	9.67
10/27	87	0.0	DL	22.34	7.36

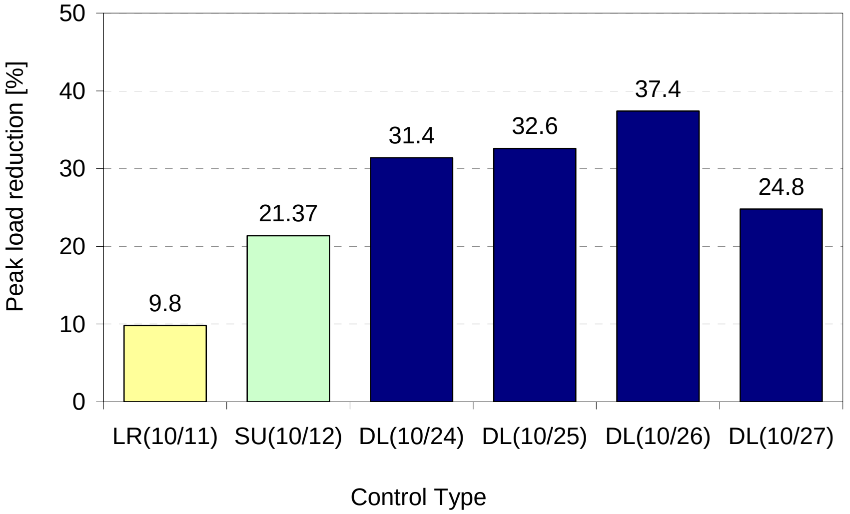


Figure 16. Comparison of peak load reductions with different cooling setpoint controls of LR, SU, and DL controls

Comfort Survey Results

Results

There were three unique characteristics to this comfort study:

(1) the occupancy time of survey respondents was relatively short
(2) the quantity of votes collected on any given day was small (between 6 and 28 votes total) but a large number of days were sampled
(3) the difference between indoor and outdoor temperature due to the desert climate where the bank is located (delta T from -18 to 33 deg F) was often large.

In this bank, customers typically did not queue before seeing a teller and the time spent in the bank was generally less than the 15 minute time-period required for the body to acclimate from an outdoor to indoor temperature. It is also much less than the time needed to experience the shape of the DL temperature profile. As a result, the votes cannot record an occupant’s response to a DL temperature profile over time but rather indicate a response to a near-instantaneous sensation. This instantaneous reaction would be the bank customer’s response to DL strategies. Due to the small quantity of votes logged for any given day, it was not possible to make meaningful statistical comparisons between a single test day and corresponding baseline day. However, because the votes logged represent a response to a near-instantaneous sensation, the votes logged from all days (test and non-test) can be pooled to generate a statistically significant data set.

Goal

The goal of our analysis was to define setpoint boundaries for an acceptable percentage of thermal discomfort for comparison with the upper and lower setpoint bounds implemented in the DL tests (pre-cool to 70 deg F, warming to upper bound of 78 deg F). A further goal was to examine if the difference between indoor and outdoor temperature influenced customers' tolerance of the indoor temperature.

Visual Analysis of the data

Results of the comfort survey show a high degree of variability between respondents voting at any given interior temperature as shown below in Figure 17. The survey response corresponds to the five-point scale: (5) Too warm! it bothers me, (4) Warm, but it does not bother me, (3) Just right, (2) Cool, but it does not bother me, (1) Too cool! it bothers me.

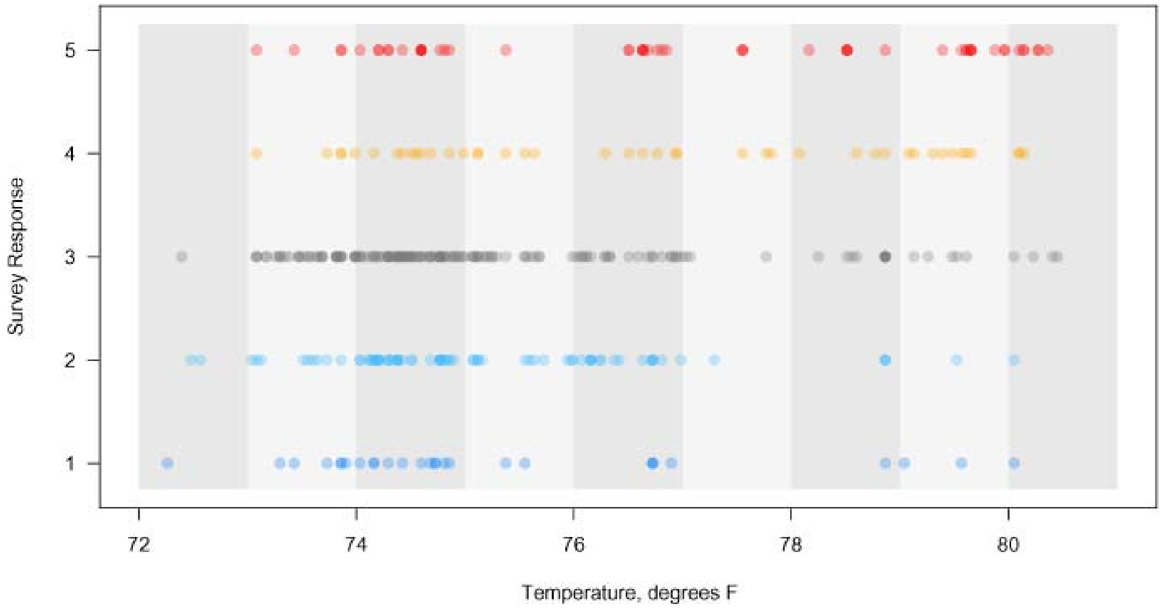


Figure 17. Plot of indoor temperature and survey response consisting of all data from both test days and non-test days. (370 data points)

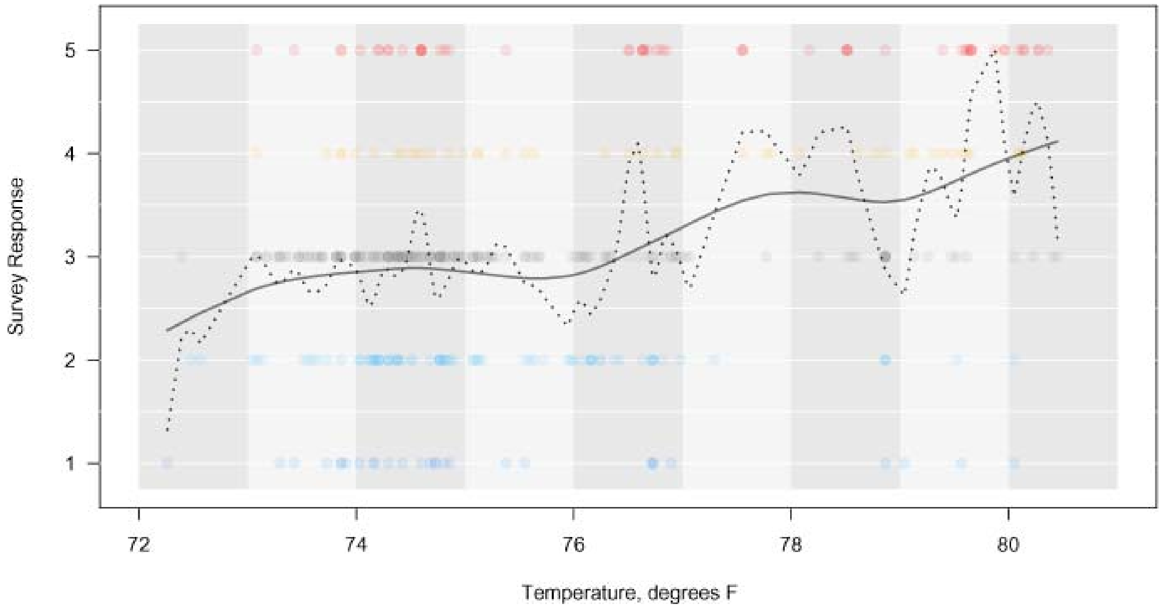


Figure 18. Plot of indoor temperature and survey response representing all data from both test days and non-test days with two splines applied. (370 data points)

In order to explore the data for a general trend in voter response to indoor temperature, we looked at how voters responded within a small temperature range (between 72 and 73 degrees, 73 and 74 degrees etc.) and calculated the mean vote within each temperature range. Because computational methods allowed us to calculate the mean vote within much smaller temperature bands, we used a spline function where any point on the spline represents the mean vote at that particular temperature on the x-axis. The reason the slope of the dotted spline varies up and down is because within any small temperature range, there were very few people voting, so concentrations of any one type of vote had a strong effect on the mean. The solid spline “smoothes out” these variations and illustrates the general trend of increased warmth perception as the indoor temperature increases.

Because we wanted to find a parametric model to represent the data we collected, we explored the distributions of each response category: (5) Too warm! it bothers me etc. Figures 19 and 20 illustrate the similarity in temperature range between survey responses (1, 2, 3) and (4, 5) showing that a vote of (4) “Warm” and (5) “Too warm! it bothers me” were responses to the same indoor thermal conditions.

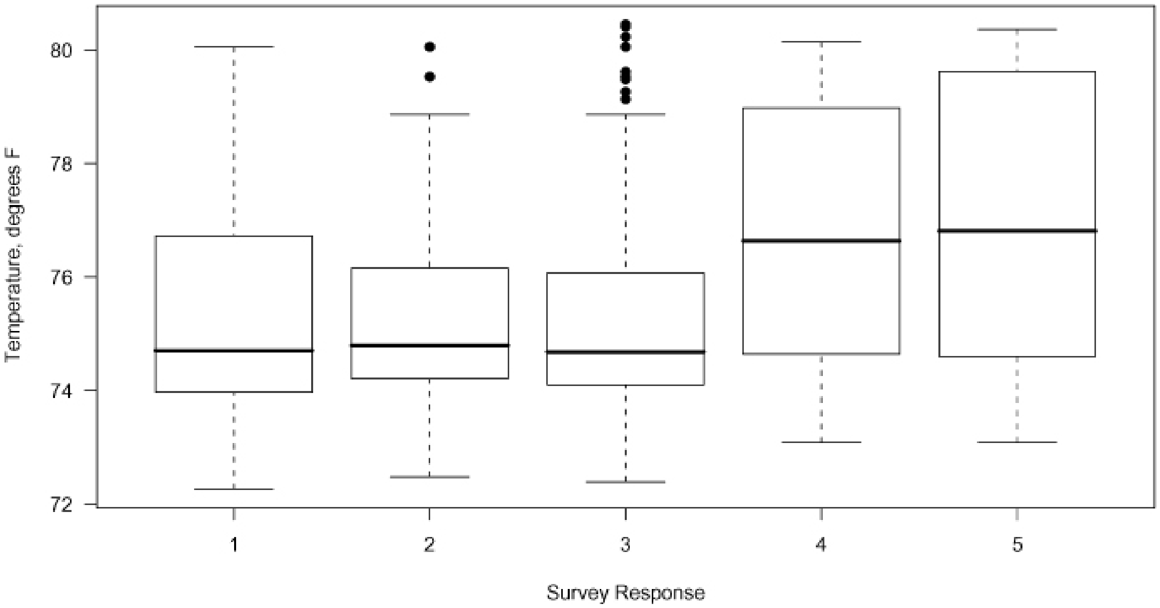


Figure 19. Box and whisker plot of indoor temperature and survey response representing all data from both test days and non-test days.

In the above box and whisker plot, the dark line inside each box represents the median temperature recorded for each respective vote category. The median is found by arranging all the observations from lowest value to highest value and picking the middle one. For category (1) Too cool! it bothers me, for example, the median temperature was approximately 74.6 degrees. The box around the median represents 50 percent of the votes for that category. It is interesting to note in this plot that the median for categories (1), (2) and (3) are nearly the same (about 74.4 to 74.6 degrees). And, the distributions of the middle 50 percent of each category (the box), are also very similar. This indicates that votes of (1), (2), or (3) on our auto-polling station coresponded to very similar thermal condtions. That means that given a certain temperature, it was just as likely to get a vote of (1) as it was a vote of (2), or (3) from the occupants. There is a similar relationship between votes of (4) “Warm” and (5) “Too warm! it bothers me.” In the plot below, (Figure 20) which is another way of looking at each vote category, the close relationship of the solid lines (votes 4, and 5) illustrate that over the course of the test, no matter what the temperature was, a voter was about just as likely to vote (4) as he or she was to vote (5).

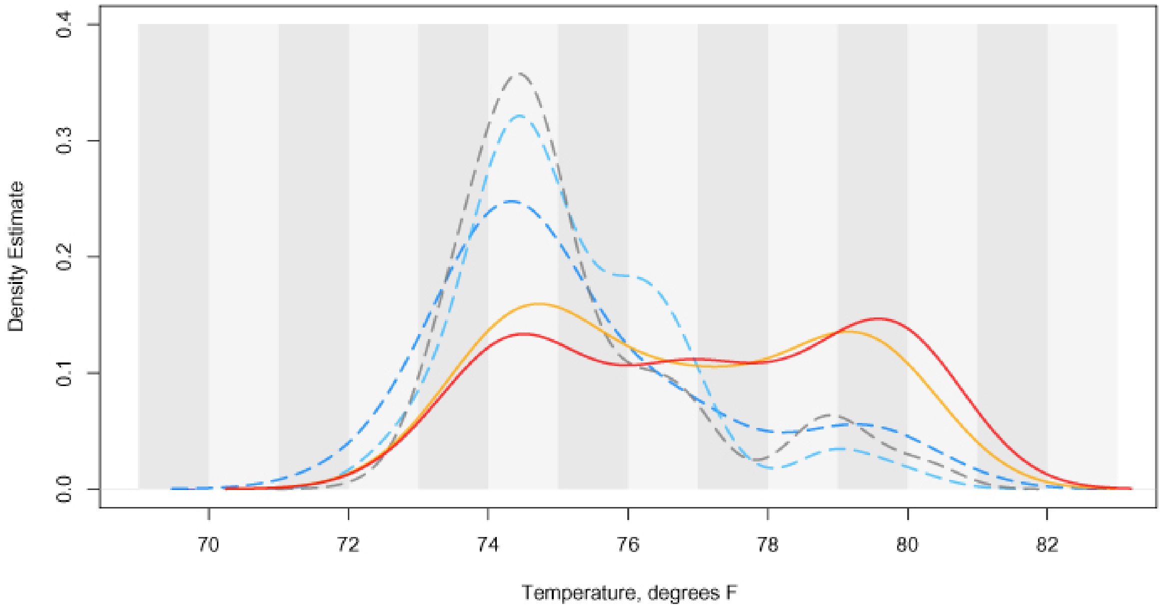


Figure 20. Density plot of indoor temperature representing all data from both test days and non-test days. Dotted lines = votes 1, 2, 3. Solid lines = votes 4 and 5.

Logit Regression of Comfort Data

To predict the probability of thermal discomfort, we used a logit model and regressed votes (4 and 5) against votes (1, 2, 3) to predict "warm," and (1, 2) against (3, 4, 5) to predict "cool."

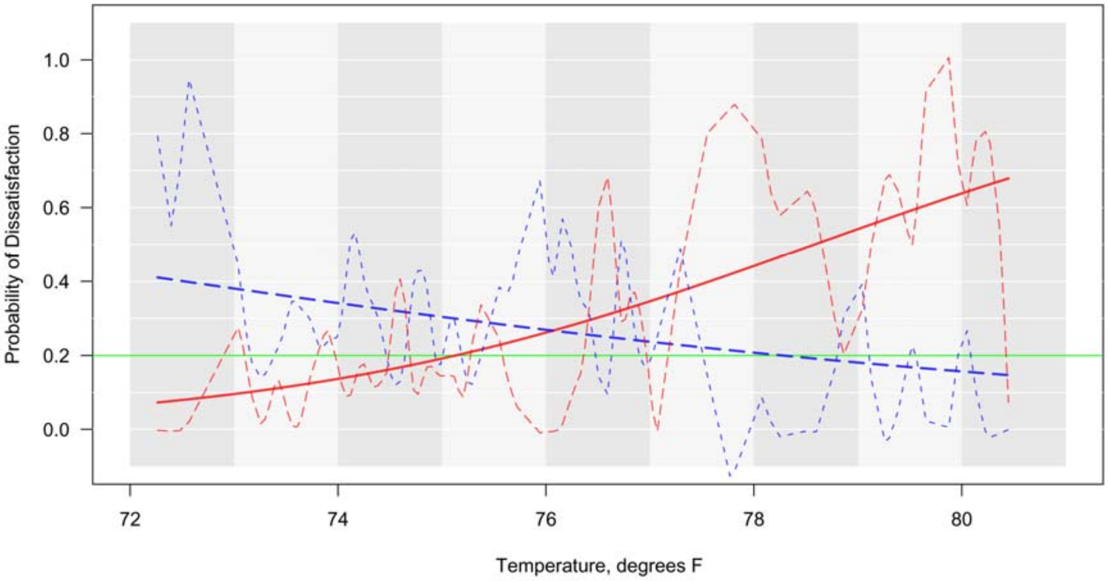


Figure 21. Logit plot of "cool" (dashed blue curve = votes (1, 2)) and "warm" (red curve = votes (4, 5)) from data set of all votes for all test and non-test days. The green line represents the 20-percent dissatisfaction threshold cited in ASHRAE and ISO indoor environmental standards. The dashed splines represent the actual data (short dash = probability of "cool", long dash = probability of "warm")

It is important to note that this plot was made by pooling the responses (5) "too warm! it bothers me" with (4) "warm, but it does not bother me" and (1) "too cool! it bothers me," with (2) "cool, but it does not bother me." These produce a strong logit plot. However, because the responses that make up these (1,2) and (4,5) groupings (see Figures 19 and 20), the logit model does not fit well when the highest and lowest *individual* responses (either 1 or 5) are regressed against the other four. We were unable to fit a parametric model to predict the probability of "too warm! it bothers me," or "too cool! it bothers me."

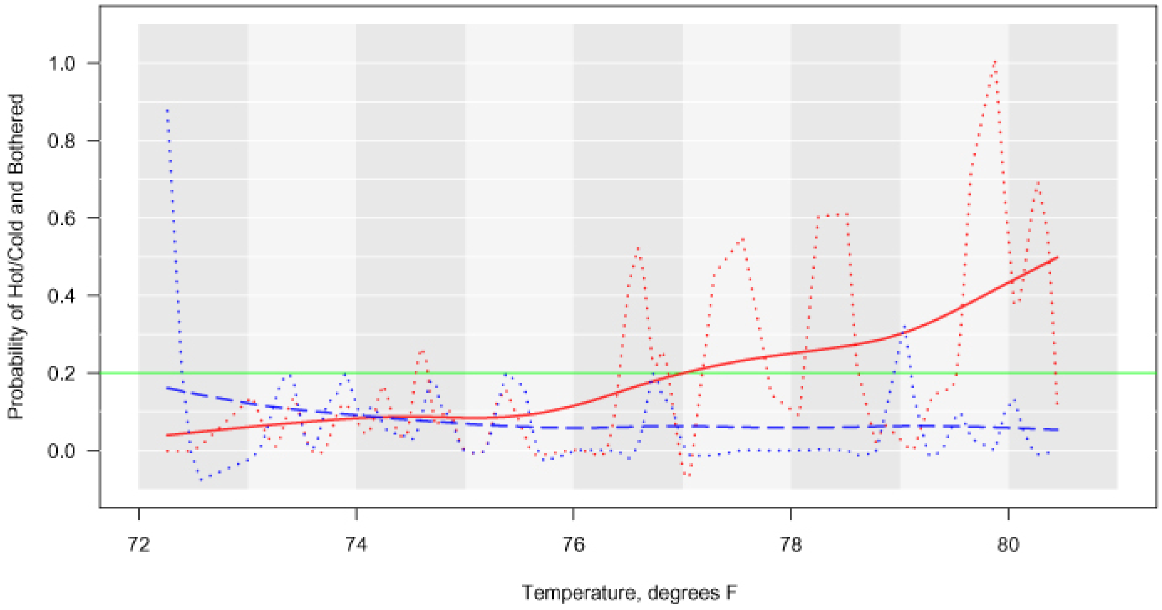


Figure 22. Plot of vote 1: “too cool! it bothers me” (dashed blue curve) and vote 5 “too warm! it bothers me” (red curve) from data set of all votes for all test and non-test days.

To estimate the probability of “too warm! it bothers me,” and “too cool! it bothers me” for a given temperature, we applied splines to approximate the mean probability of dissatisfaction. Given the highly variant responses at any given temperature, these splines can only be interpreted as approximations.

Conclusions about thermostat setpoints

If the setpoints used in the DL tests are evaluated using Figure 21, we can predict that greater than 40-percent of the population will respond “cool”, (ie vote 1 or 2) at the low setpoint (70 deg F; actual temperature 72 deg F). Using Figure 22, we can estimate that the probability of “too cool! it bothers me,” will approach 18-percent at the low set point. Similarly, using Figure 21 we can predict that greater than 40-percent of the population will respond “warm” at the upper set point (78 deg F), and using Figure 22, we can estimate that the probability of “too warm! it bothers me,” will approach 23-percent at the upper set point.

Possible comfort effects of the indoor-outdoor temperature difference

Because of the short occupancy time of the occupants, we wondered whether the transition of respondents from a hot exterior thermal environment (such as might occur during a DR event) to a relatively cooler indoor environment would have an effect on the respondent's tolerance of the indoor temperature. There is no literature addressing this possible effect. Similar to the responses to indoor temperature, the response to delta T was highly variable for any given delta T.

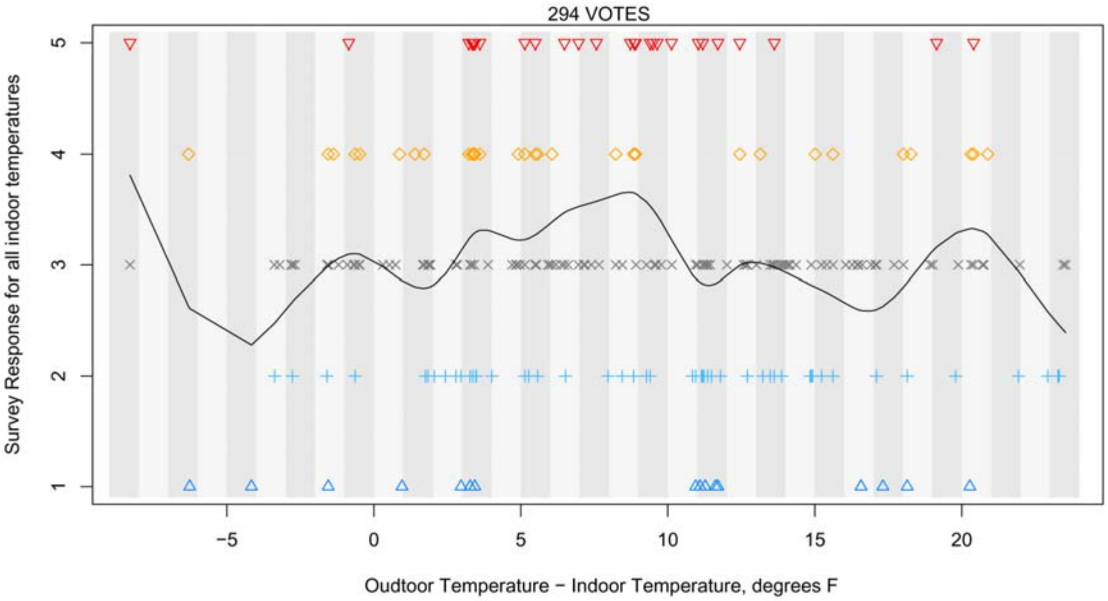


Figure 23. Analysis of delta-T and survey response for all data points. The smoothed spline approximates the mean value of the survey response at each value of delta-T. 294 data points.

Examination of these data revealed no significant influence of outdoor temperature or the outdoor/indoor temperature difference on a given customer's votes concerning the indoor thermal environment. The data was examined by looking at the mean voter response as the difference in indoor and outdoor temperature increased. If the delta-T affects the vote, then the spline shown on the plot (which approximates the mean vote at every value of delta-T) will have a generally positive or negative slope from where delta-T equals zero to where delta-T is the highest. A positive slope indicates that when the delta-T increases (such as on a very hot day), then there is a corresponding increase in thermal discomfort in the "too hot" direction. Conversely, if the spline has a negative slope, then as the delta-T increases there is a corresponding increase in thermal discomfort in the "too cold" direction.

Because our data showed that customers were the least bothered (figure 22) when the indoor temperature was 74 degrees F, we took a subset of our data and examined if the delta-T had any affect on customer tolerance when the indoor temperature was between 73 and 75 degrees F. The below plot (where the spline is generally flat and centered on the neutral vote) indicates that the thermal comfort of the occupants remains neutral as the delta-T increases and even when the delta-T is quite large.

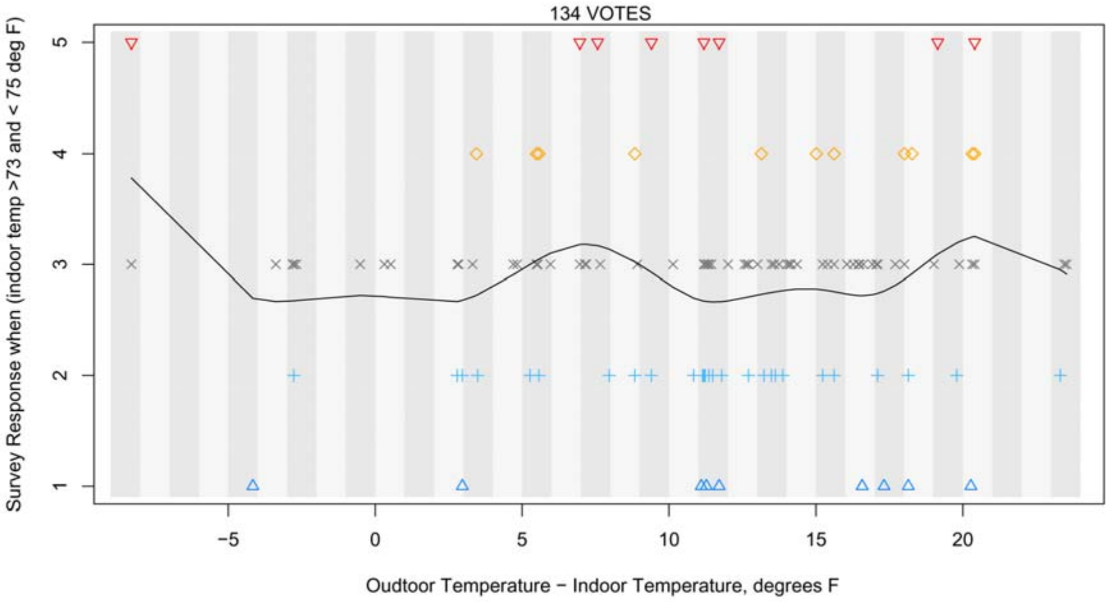


Figure 24. Analysis of delta-T and survey response when the indoor temperature was between 73 and 75 degrees F. The smoothed spline approximates the mean value of the survey response at each value of delta-T. 134 data points.

The final question we looked at was whether or not the delta-T affects occupant thermal comfort when the indoor temperature is above the optimal temperature for thermal comfort (74 degrees F), as is often the case in a DR event when the indoor setpoint is allowed to float. We wanted to see if occupants would be more willing to tolerate a warmer indoor temperature (between 76 degrees and 80 degrees F) if the outdoor temperature exceeded the indoor temperature by a certain margin. If occupants are willing to accept a warmer indoor temperature on days when the delta-T is high (which are likely to be DR days) then set backs can be implemented without bothering most occupants. However, the below figure, which examines occupant votes when the indoor temperature is between 76 degrees and 80 degrees F, shows a general increase in thermal discomfort in the "too warm" direction. Because there are relatively few data points used in this analysis, it is difficult to show any trend with much certainty.

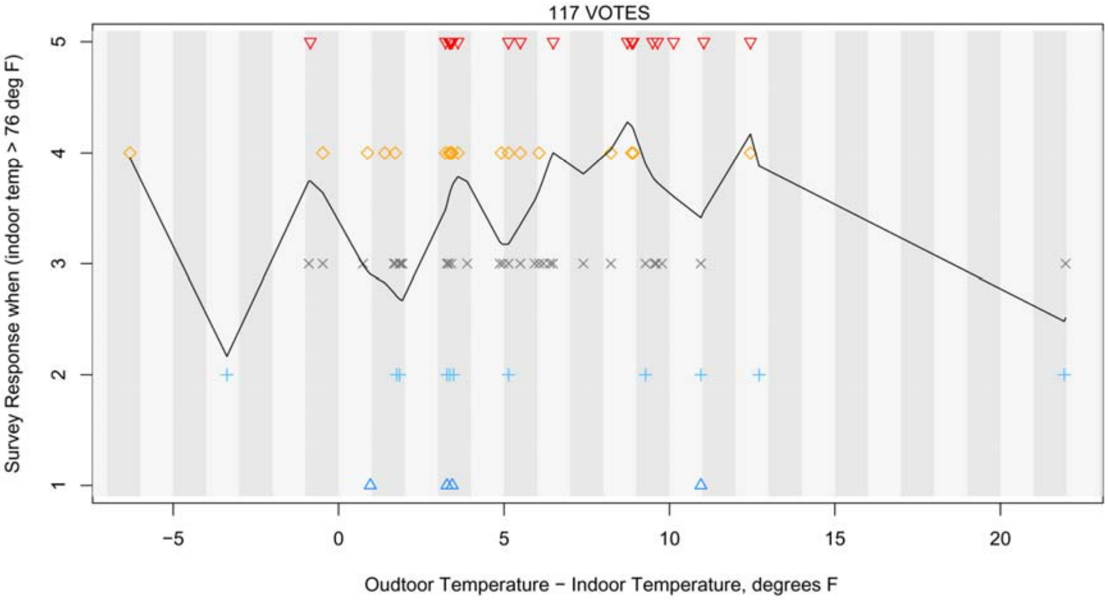


Figure 25. Analysis of delta-T and survey response when the indoor temperature was between 76 and 80 degrees F. The smoothed spline approximates the mean value of the survey response at each value of delta-T. 117 data points.

Lessons Learned

In evaluating the effect of demand-limiting on occupant comfort, these results represent a mix of the perceptions of bank customers and employees. It might have been better to collect separate data sets for employees and customers (as we did in some of the banks that were not tested), to separate out the issue of residency time. In the end, because occupant response to a DL strategy occurs over a period of hours (a temperature profile as opposed to an instantaneous sensation), it is probably safe to say that the key comfort consideration will be that of the building staff, who occupy the building for a sustained period of time.

CONCLUSIONS

A demand-limiting (DL) strategy that uses building precooling and setpoint adjustments was tested in a small building in Palm Desert, California. The precooling temperature was set to 70ºF from 6am to 12pm and setpoint temperatures during an on-peak period from 12pm to 6pm were adjusted from 70ºF to 78ºF. The DL control was tested for four days in October. The test results indicated that more than 30% reduction in peak air conditioner load was possible for a 6-hour demand-limiting. The average peak load savings was 0.76W/ft^2 for the test building.

Comfort evaluations were performed for the facility during the field tests, and baseline data was collected during the days between the tests. The comfort survey illustrated a highly variable response to the indoor environment on base days as well as test days. This might be characteristic of buildings such as banks that have a relatively short customer occupancy time, although this is a new finding. The difference between outdoor and indoor temperature did not significantly affect customers' perception of the indoor temperature. In future studies of buildings that have relatively short customer occupancy time, it would be useful to collect data from employees rather than customers, as the employee response to thermal sensation over an extended period of time will better describe the affect of the thermal profile generated by the DL strategy.

This field test demonstrated that small commercial buildings can be good candidates for utilization of thermal storage in building mass to reduce peak demands. Additional work is necessary to thoroughly evaluate the impacts of the strategy on peak load reduction and comfort of occupants. It would be useful to study the effects of precooling duration, precooling temperature, comfort temperature range, time interval of setpoint temperature resetting, and ambient temperature conditions. Furthermore, more small commercial buildings that have diverse thermal load characteristics should be tested.

In particular, it is important to consider hotter weather. None of the test days included really hot weather where the cooling loads were high relative to the equipment cooling capacity. It is expected that hot days would result in similar absolute reductions in peak power consumption, but lower percentage reductions for use of building thermal mass as compared with cooler days. It also important to consider comfort impacts for thermal strategies implemented on hotter days.

Peak power reduction associated with control of building thermal mass could also be sensitive to the number of air conditioners and stages of capacity control at the site. The power consumption associated with air conditioning has larger short-term fluctuations when there are fewer capacity steps due to compressor cycling. Power fluctuations due to on/off cycling of single-stage equipment are evident in the 15-minute data presented in Figures 9, 11, 13, 14, and 15. Smaller fluctuations would be expected for a larger building with more air conditioners or if each of the units had multiple stages of control. Furthermore, lower peak power could be achieved if the run times of the air conditioners were coordinated.

ACRONYMS

DL	demand limiting
delta-T	temperature difference
LR	linear rise
NS	night setup
RH	relative humidity
SU	step up
WA	weighted averaging

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Lee, K.H. and Braun, J.E., 2006c, Development of Methods for Determining Demand-Limiting Setpoint Trajectories in Commercial Buildings Using Short-Term Data Analysis, Proceedings of the 2006 IBPSA-USA Conference at MIT, Boston, MA.

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APPENDIX

ENVIRONMENTAL CONDITIONS AND OCCUPANT RESPONSES ON ALL TEST DAYS AND RESPECTIVE BASELINE DAYS

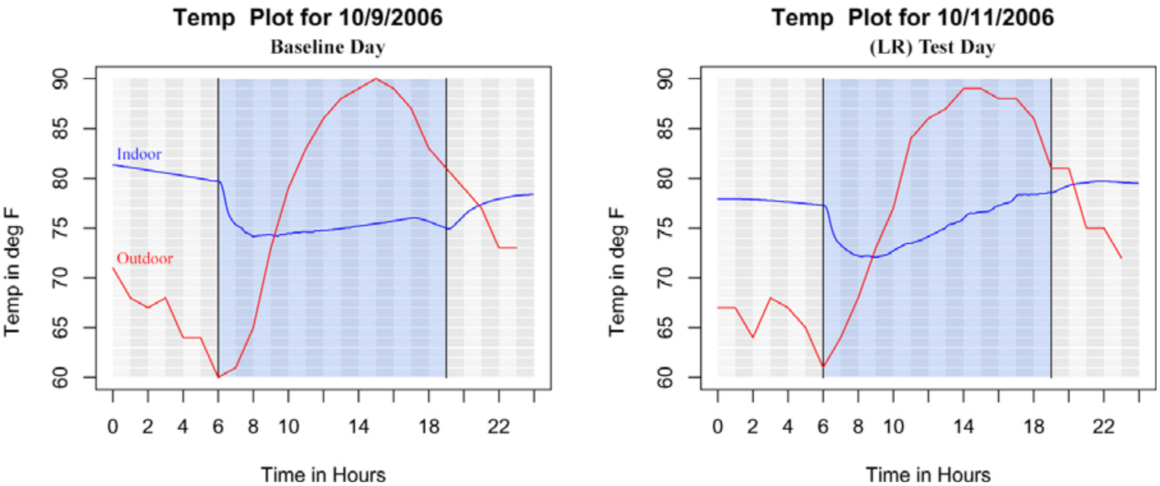

Figure 24. Comparison of indoor/outdoor temperature between baseline day (10/9/2006-BL) and test day (10/11/2006-LR). No comfort data was collected on this test day due to a malfunction with the voting station.

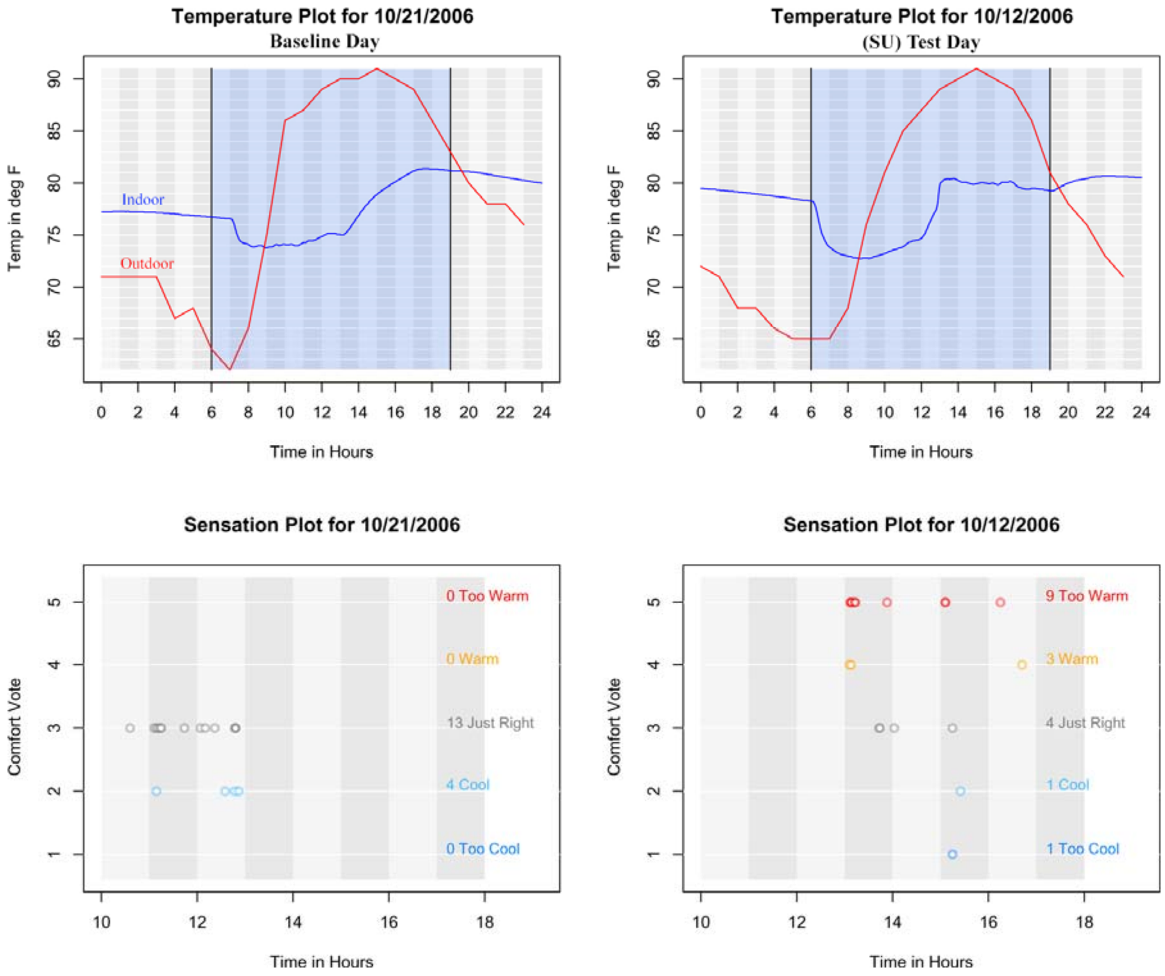

Figure 25. Comparison of indoor/outdoor temperature and comparison of comfort votes between baseline day (10/21/2006-BL) and test day (10/12/2006-SU). Because no comfort data was collected on 10/9/2006, 10/21/2006 was substituted because it had comparable outdoor weather conditions.

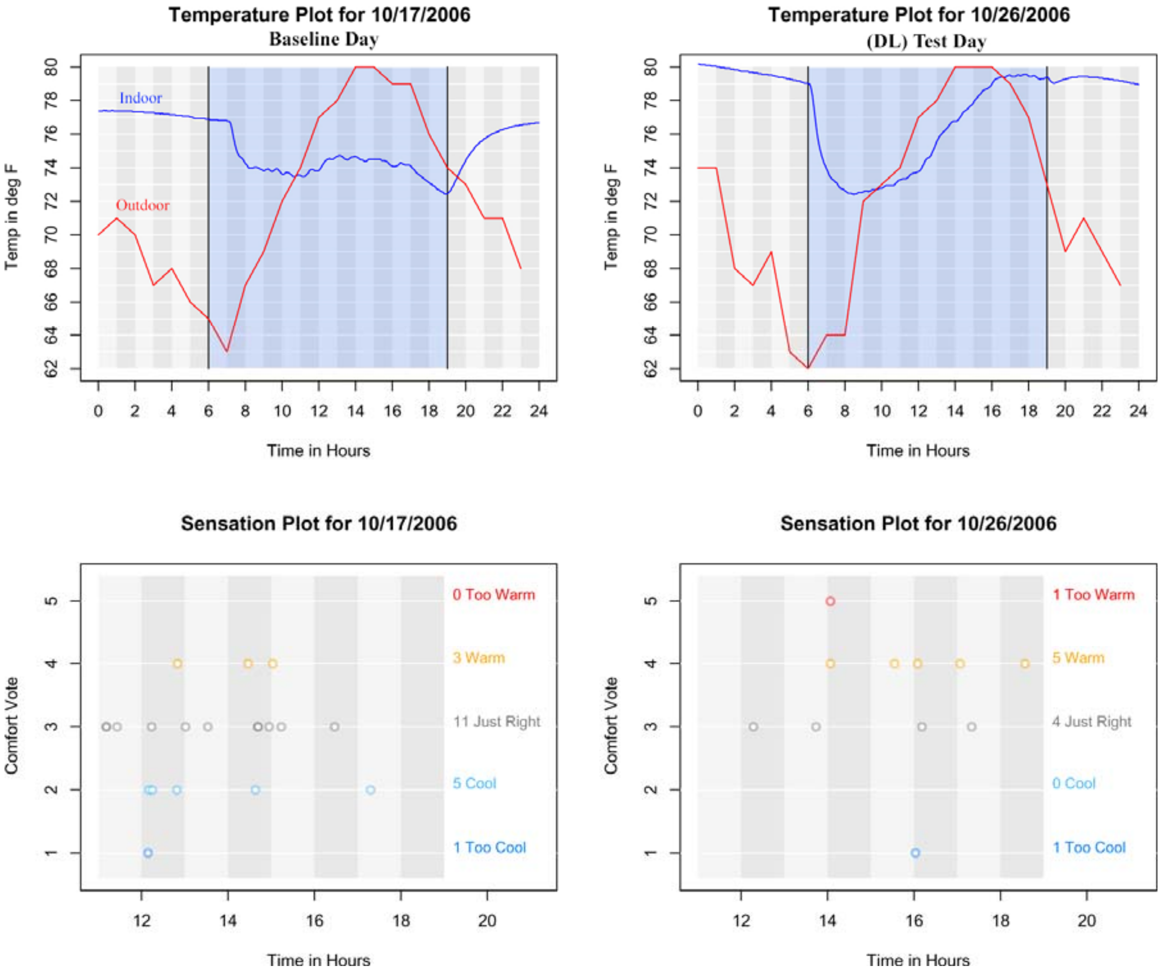

Figure 26. Comparison of indoor/outdoor temperature and comparison of comfort votes between baseline day (10/17/2006-BL) and test day (10/26/2006-DL)

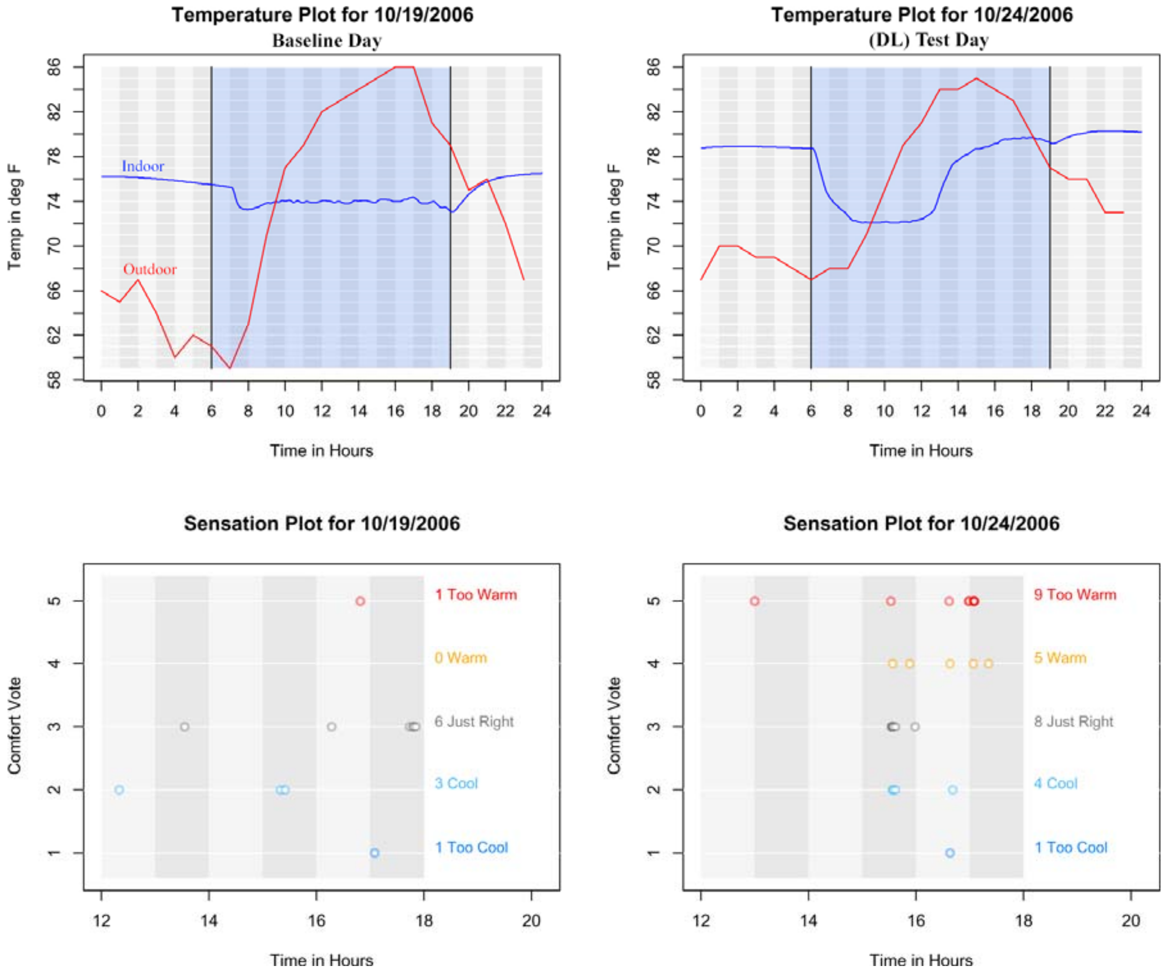

Figure 27. Comparison of indoor/outdoor temperature and comparison of comfort votes between baseline day (10/19/2006-BL) and test day (10/24/2006-DL)

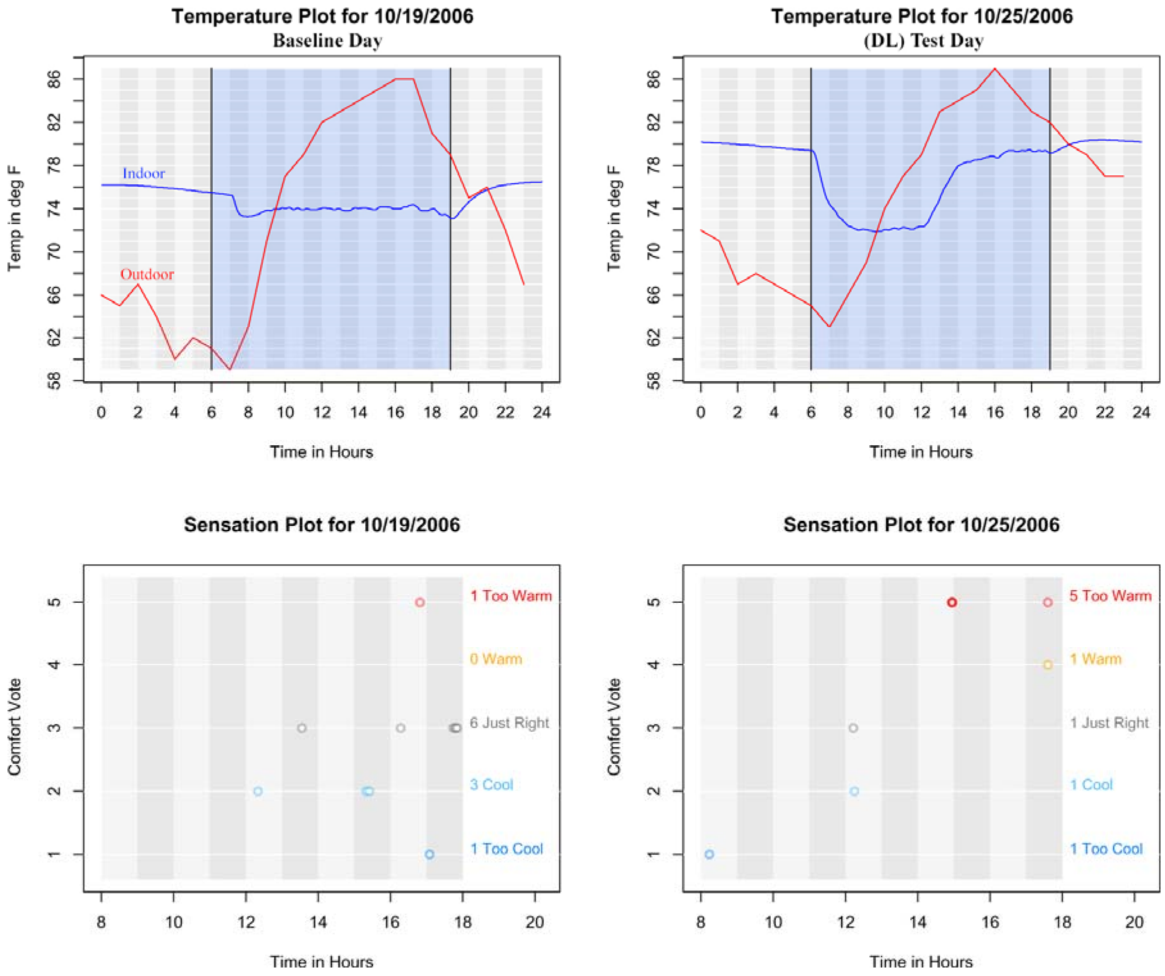

Figure 28. Comparison of indoor/outdoor temperature and comparison of comfort votes between baseline day (10/19/2006-BL) and test day (10/25/2006-DL)

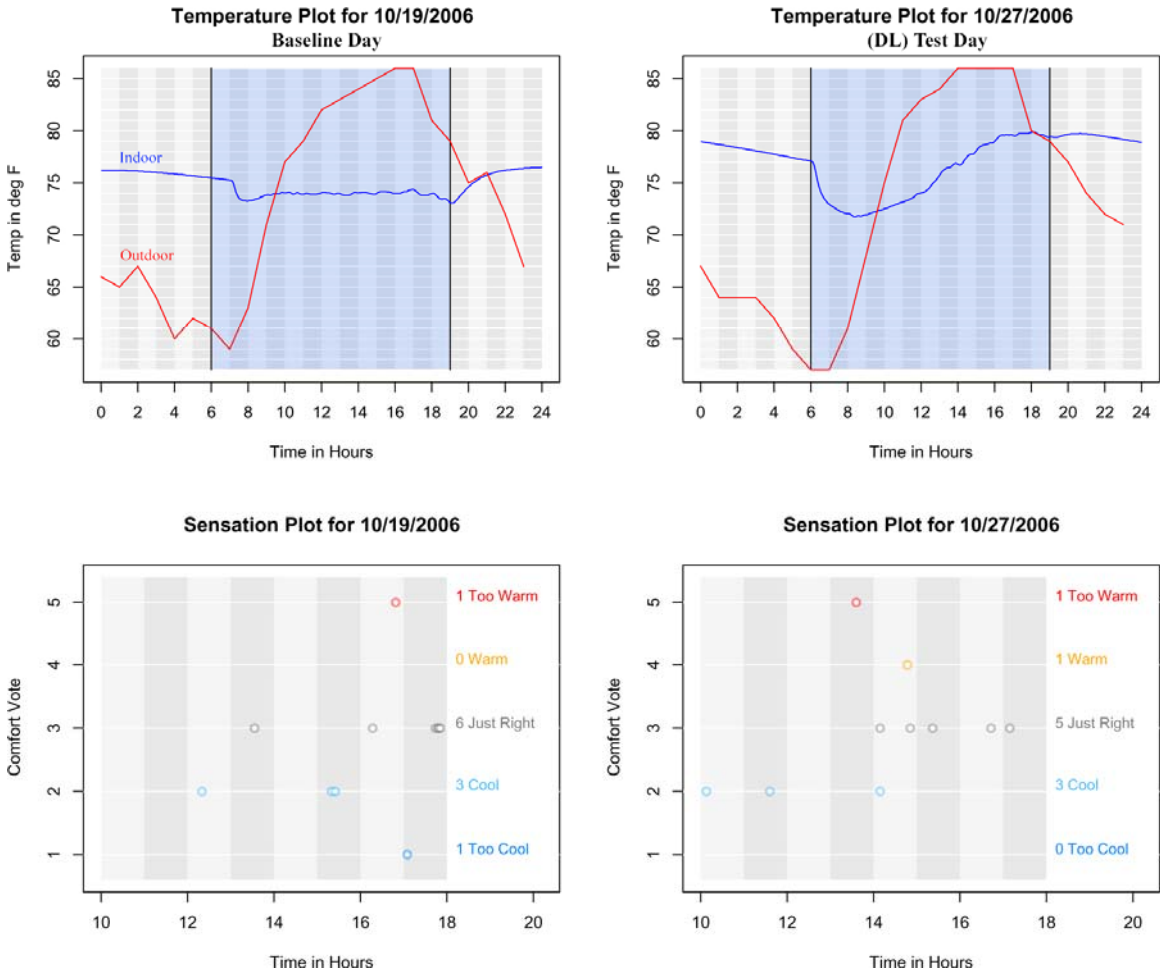

Figure 29. Comparison of indoor/outdoor temperature and comparison of comfort votes between baseline day (10/19/2006-BL) and test day (10/27/2006-DL)