Joint-Frequency Bins versus Conventional Bin Weather Data in Analysis of HVAC System Operation

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ABSTRACT

Often in simplified energy analysis the use of bin weather data is employed for a more time efficient and better organized analysis than using the full 8760-hour annual weather data. It has been suggested that joint-frequency bins be used instead of conventional bin data.

Joint-frequency bins of dry bulb temperature and humidity ratio and conventional bin data are used in the analysis of the operation of four different HVAC systems in a prototype building using weather data from four climatic regions. In the case of 10% ventilation air, the analysis shows less than 3% difference in cooling between the use of the different bin methods. An increase of ventilation air to 40% increases the percent difference up to 10% difference in cooling requirements. From this study the use of joint-frequency bins has relative added value to the analysis of HVAC system operation depending on whether the system is dominated by ventilation loads.

INTRODUCTION

Often in simplified energy analysis the use of bin weather data is employed for a more time efficient and better organized analysis than using the full 8760-hour annual weather conditions. The criteria for binning weather data varies depending on location, year of analysis and other project specific details. Bin weather data involves two different weather variables, some examples include; dry bulb and dew point temperatures, dry and wet bulb temperatures, or temperature and a humidity variable. Typically binned weather data is generated by sorting one weather variable into bins while the mean coincident value of another variable is determined for each bin. However, it is known that conventional bin analysis does not accurately represent extremes in weather data, which may be the case when the climate is better represented by two variables, such as in hot and humid regions. To avoid this problem it is recommended to use a joint-frequency bin scheme for the weather data. The joint-frequency technique groups the number of shared occurrences of two weather variables into bins, for example dry-bulb temperature and humidity ratio. This study aims to determine to what extent the aforementioned assertion related to the joint bin distribution could be applicable to analyze and improve the performance of a building. Therefore, two weather distributions, joint-frequency bins and conventional bins, are used to determine the performance of four of the most typical HVAC system configurations in a prototype building: dual-duct variable air volume (DDVAV), single duct variable air volume (SDVAV), dual-duct constant air volume (DDCV) and single duct constant air volume (SDCV).

METHODOLOGY

To capture the impact of some differences in climate, cities were chosen from four different climatic areas: Houston, TX representing humid subtropical (hot & humid) climates, Albuquerque, NM representing semiarid climates, Phoenix, AZ representing desert (hot & dry) climates and Chicago, IL representing humid continental-hot summer climates. Climate descriptions are according to Encarta Online 2009. For each city bin data distributions were determined by three different methods: joint-frequency bin distribution using outside dry bulb temperature (T_o) and outside humidity ratio (ω_o), typical bin distribution using T_o with mean-coincident ω_o and similarly using ω_o with mean-coincident T_o. Each temperature bin spans 5 degrees Fahrenheit and each humidity bin spans 5 grains of water vapor per pound. The bin data distributions for each location were generated using an excel based tool developed by Jones, et al (2009) and using typical meteorological year 2 weather data files produced by the U.S. National Renewable Energy Laboratory (2009).

The ventilation load analysis was employed as a verification of the bin data that would be used for the system performance analysis. For each city the Ventilation Load Index (*VLI*), developed by Harriman, et al (1997) was calculated using all 8,760 hours of data as well as the three sets of bin data previously described. The *VLI* is the annual load generated by one cubic foot per minute (cfm) of fresh air brought from the weather to space-neutral conditions (defined as 75 deg F, 50% relative humidity). The sensible *VLI* and latent *VLI* are calculated using the following equations, as represented by Cohen et al (2000). Where T_o is the outside dry bulb temperature, T_i is the space neutral temperature, ω_o is the outside humidity ratio, ω_i is the space neutral humidity ratio, and N is the hours in each bin. The constant values presented in the equations are defined in Table 1.

Sensible VLI

$$VLI_{sensible} = \sum_{i=1}^{No.bins} \frac{4.5 \times 0.24 \times (T_o - T_i) \times N_i}{12{,}000}$$

Latent VLI

$$VLI_{latent} = \sum_{j=1}^{No.bins} \frac{4.5 \times 1{,}050 \times (\omega_o - \omega_i) \times N_j}{7{,}000 \times 12{,}000}$$

Table 1. Definitions of Constant Values in VLI Equations

Value	Definition
4.5	lbs of air per hour per cfm
0.24	specific heat of air in Btu/lb/°F
7,000	grains of water vapor per lb
1,050	heat of vaporization of water at standard temperature and pressure in Btu/lb
12,000	Btu/hr of 1 ton of air conditioning capacity

For the system analysis, spreadsheets which simulate a simplified operation of an HVAC system were prepared and used to determine the annual heating and cooling load (Claridge, 2007). These spreadsheets were developed for each system type and employ a series of equations that incorporate the operation control and parameters of the system, the sensible and latent load information and the bin weather data to calculate the annual heating and cooling loads. The HVAC information input to the simplified simulation allows calculation of the room supply temperatures, mixed air temperature, humidity ratios and coil loads. Each of the four typical systems was analyzed for each city using the previously defined two different forms of bin data: typical bins using T_o with mean-coincident ω_o and joint-frequency bins using T_o and ω_o. The load and system information used for the analysis is summarized in Table 2. The performance analysis was completed using 10% ventilation air as well as 40% ventilation air.

Table 2. Load and System Information

Floor area	150,000	sqft
Floor area per person	160	sqft/person
Sensible heat gain from a person	250	Btu/hr-person
Latent heat gain from a person	105	Btu/hr-person
Ventilation air	10 and 40	%
Interior zone temperature	75	°F
Design fan power	108	HP
Minimum supply air flow	0.4	cfm/sqft

BIN DATA VERIFICATION

In order to verify the bin data that was used for the system performance analysis the previously defined index was used. The Ventilation Load Index was calculated for each city and is shown in Figure 1 for Houston, Figure 2 for Phoenix, Figure 3 for Albuquerque and Figure 4 for Chicago. The sensible *VLI* is usually underestimated by humidity bins while the latent *VLI* is underestimated by temperature bins. This discrepancy is very apparent in the *VLIs* for Phoenix where there is 0 latent *VLI* according to the temperature bin analysis and Albuquerque where there is 0 latent *VLI* and 0 sensible *VLI* according to the temperature bin and humidity bin analysis, respectively. In comparison to the full 8,760 hour *VLI* analysis, the Chicago analysis percent difference between latent *VLIs* is 28%, while the sensible *VLI* percent difference is 71%. Though the Houston analysis shows less noticeable discrepancies, the latent *VLI* percent difference is 5% but the sensible *VLI* percent difference is 26%. The joint-frequency *VLI* analysis produces similar results to the full 8,760 hour *VLI* analysis. These observations agree with the literature on *VLI*, (Harriman, et al 1997 & Cohen, et al 2000) and provide verification for the bin data used.

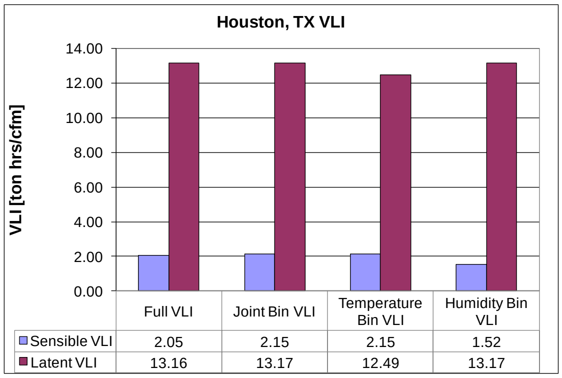

Figure 1. Houston VLI Comparison

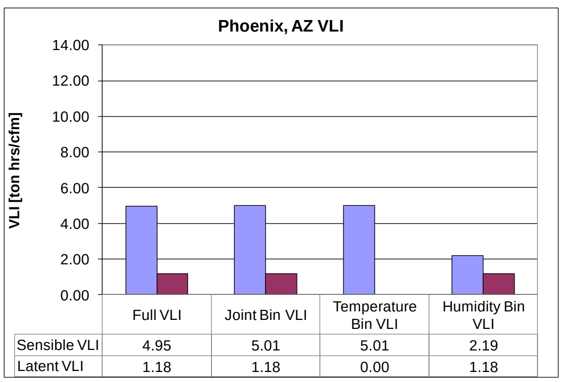

Figure 2. Phoenix VLI Comparison

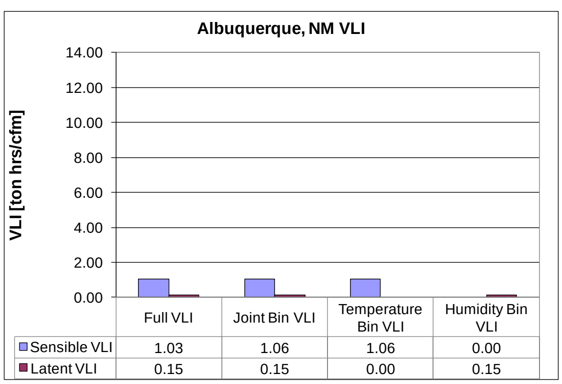

Figure 3. Albuquerque VLI Comparison

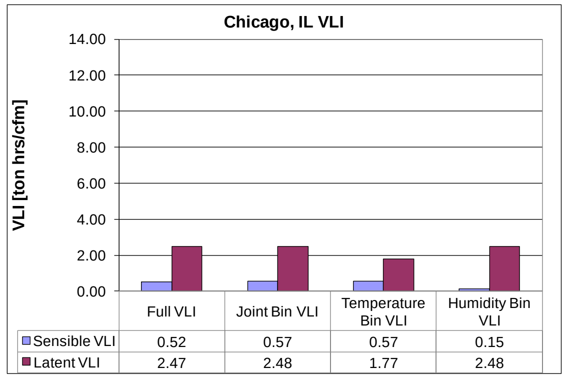

Figure 4. Chicago VLI Comparison

SYSTEM PERFORMANCE ANALYSIS

For the system analysis using 10% ventilation air, the T_o bins versus the joint-frequency bins produce similar results for systems in Houston; with less than 1% difference between cooling loads and no difference in heating loads. In Phoenix, the difference between cooling loads is 3% and there is no difference in heating loads for the VAV systems. The difference for cooling loads in the constant volume systems is less than 1%. In Albuquerque there is a 1-2% difference between cooling loads and no difference in heating loads. The Chicago analysis produced the same percent difference results as the Houston analysis.

For the system analysis using 40% ventilation air, as expected, the increase of ventilation air increased the difference between cooling loads however there was no effect on the difference between heating loads. There was a slight increase in the cooling load difference for Houston but still less than 2% difference. A higher increase was found for Albuquerque with a maximum percent difference of 5.3%. In Chicago the maximum percent difference was 6.3% only slightly higher than Albuquerque. In Phoenix the percent difference is up to 10% for VAV systems but under 2% for CV systems.

The annual heating and cooling loads for Houston, TX are shown in Figure 5 for the DDVAV analysis, Figure 6 for the SDVAV analysis, Figure 7 for the DDCV analysis and Figure 8 for CVRH analysis. Each figure compares the 10% ventilation case with the 40% ventilation case, providing the percent difference between the conventional bin (T_o bins) analysis and the joint-frequency bin analysis.

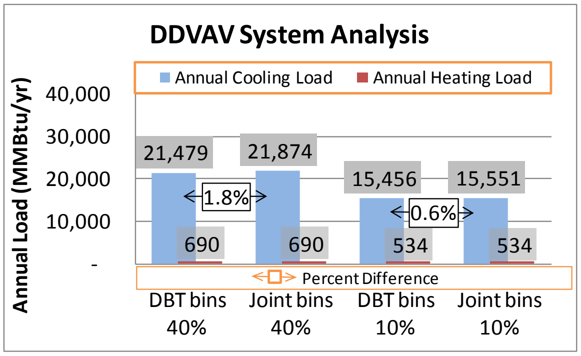

Figure 5. Houston, TX DDVAV System Analysis

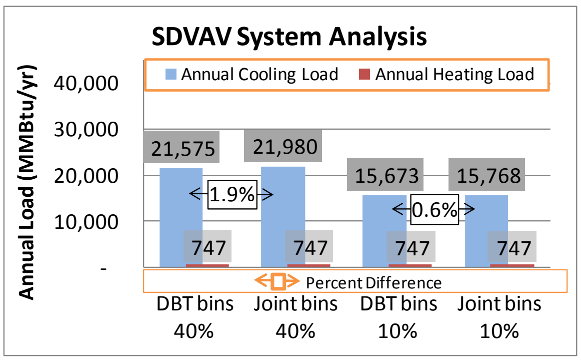

Figure 6. Houston, TX SDVAV System Analysis

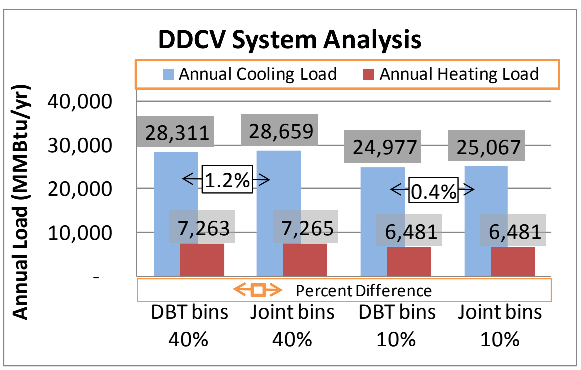

Figure 7. Houston, TX DDCV System Analysis

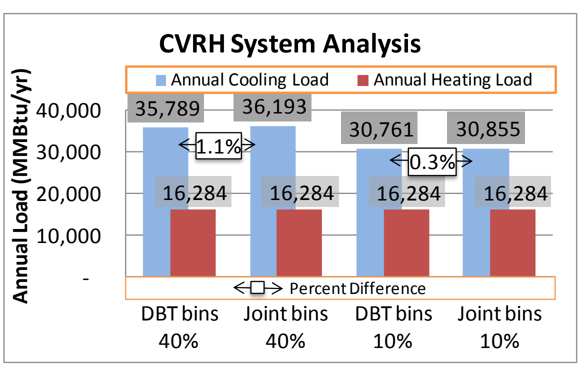

Figure 8. Houston, TX CVRH System Analysis

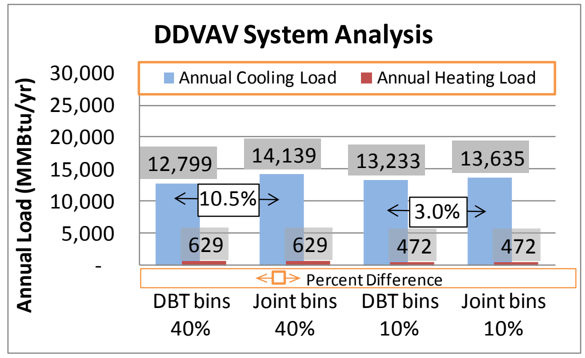

Figure 9. Phoenix, AZ DDVAV System Analysis

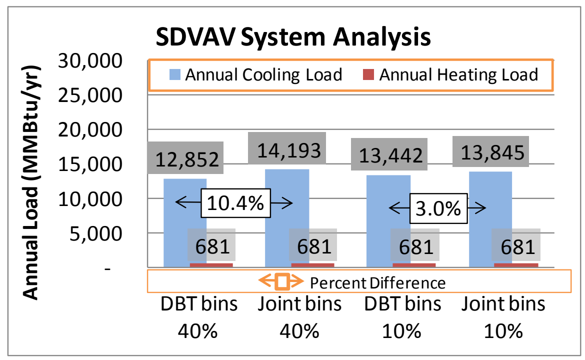

Figure 10. Phoenix, AZ SDVAV System Analysis

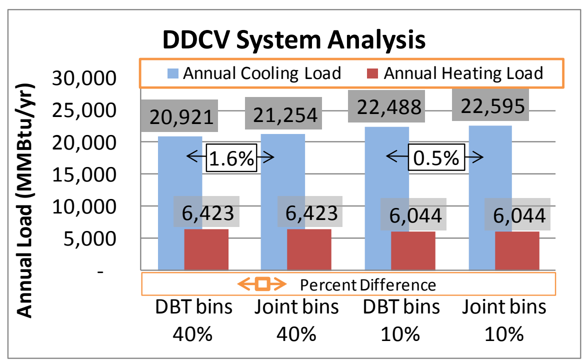

Figure 11. Phoenix, AZ DDCV System Analysis

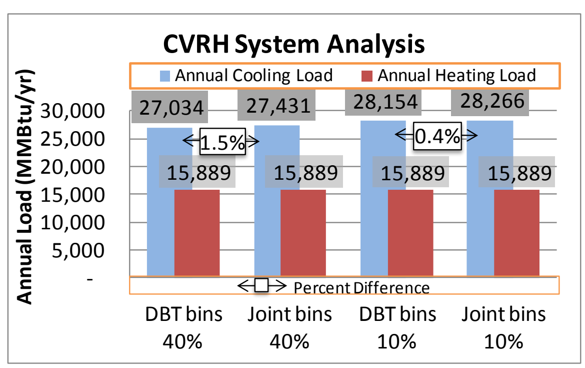

Figure 12. Phoenix, AZ CVRH System Analysis

The annual heating and cooling loads for Phoenix, AZ are shown in Figure 9 for the DDVAV analysis, Figure 10 for the SDVAV analysis, Figure 11 for the DDCV analysis and Figure 12 for CVRH analysis.

HUMIDITY & LOAD ANALYSIS

The differences in the conventional bins and joint-frequency bins have been attributed to extreme weather conditions. However the system operation analysis provides evidence that weather extremes are not necessary to produce discrepancies between using different bin weather data methods. To determine the locust of these discrepancies the humidity ratios were analyzed as well as the annual sensible and latent loads.

The humidity ratios of the full year of weather data, conventional bins and joint-frequency bins as well as the leaving cooling coil humidity ratio (ω_{cl}) and the saturated humidity ratio (ω_{sat}) are presented graphically in Figure 13, for Houston, TX. The differences between the full year of weather data, the conventional bins and the joint-frequency bins are apparent in this plot. The area above ω_{cl} represents the region of the weather data that will impact the latent cooling load which provides the significant differences between the conventional bin and joint-frequency bin analysis.

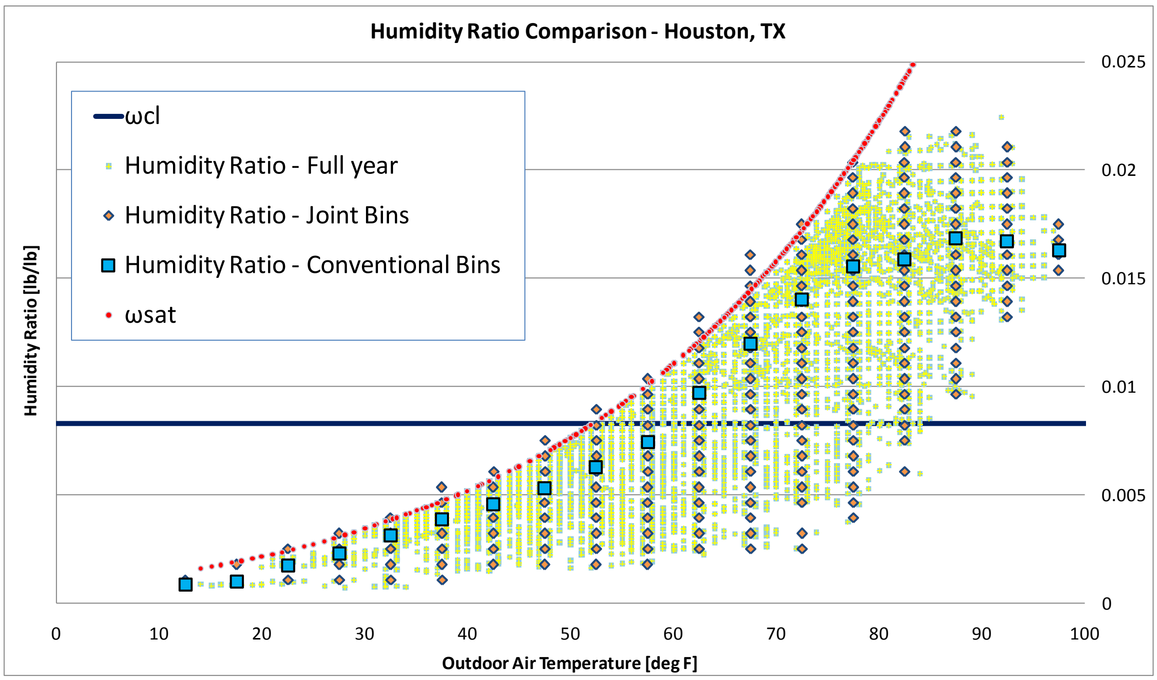

Figure 13. Houston, TX Humidity Ratio Comparison

In order to compare the sensible and latent loads between different system types the *ton hr/cfm* was calculated by dividing the total load by the total system flow in each bin then adding the values of all bins. The *ton hr/cfm* was calculated from the conventional T_o bin analysis for each city for both 10% and 40% ventilation loads. The *ton hr/cfm* for annual cooling loads in Houston and Albuquerque are presented in Table 3 and for heating loads in Table 4. Each table also contains the range of the total flow for each system. The *ton hr/cfm* for the annual cooling and heating loads for Chicago and Phoenix are presented separately in Table 5 and Table 6, respectively, since these cities have a range of flow different from the other cities. This difference is due to the higher temperature bins that are required for Phoenix weather data and lower temperature bins for Chicago. From these results it can be seen that more cooling per cfm supplied is necessary in the VAV systems however the required flow is lower. For the dual duct systems more heating per cfm supplied is necessary with less flow needed for the DDVAV system than the DDCV system. The latent load produced greater changes from 10% to 40% ventilation air than the sensible loads. Interestingly this relationship between latent load and ventilation air percentage is practically linear for constant volume systems. However for variable air volume systems the relationship is linear only up to about 45% ventilation air as seen in Figure 14 for Houston, TX.

Table 3. Ton hr/cfm for Annual Cooling Loads (10% & 40% Ventilation Air) for Houston, Albuquerque

Note: CV system flows are higher so energy use is higher than VAVs even when ton hr/cfm is lower

SYSTEM	Flow Range		10% - Houston		40% - Houston		10% - Albuquerque		40% - Albuquerque	
	minimum	maximum	Sens	Lat	Sens	Lat	Sens	Lat	Sens	Lat
	cfm		ton hr/cfm							
DDVAV	58,267	77,546	15.09	4.04	12.49	13.53	12.91	0.00	6.97	0.00
DDCV	95,525	120,701	17.55	2.70	15.55	7.93	16.58	0.00	11.69	0.00
SDVAV	66,296	77,546	15.09	4.02	12.49	13.52	12.91	0.00	6.97	0.00
CVRH		150,000	15.23	1.86	13.60	6.29	14.26	0.00	9.78	0.00

Table 4. Ton hr/cfm for Annual Heating Loads (10% & 40% Ventilation Air) for Houston, Albuquerque

SYSTEM	Flow Range		10% - Houston	40% - Houston	10% - Albuquerque	40% - Albuquerque
	minimum	maximum	Sens	Sens	Sens	Sens
	cfm		ton hr/cfm			
DDVAV	-	8,029	13.63	17.58	25.01	31.62
DDCV	29,299	54,475	13.57	15.58	22.42	27.35
SDVAV	66,296	77,546	0.94	0.94	2.09	2.09
CVRH		150,000	9.05	9.05	9.64	9.64

Table 5. Ton hr/cfm for Annual Cooling & Heating Loads (10% & 40% Ventilation Air) for Chicago

	COOLING						HEATING			
SYSTEM	Flow Range		10%		40%		Flow Range		10%	40%
	minimum	maximum	Sens	Lat	Sens	Lat	minimum	maximum	Sens	Sens
	cfm		ton hr/cfm				cfm		ton hr/cfm	
DDVAV	60,251	84,491	15.80	0.11	14.75	0.00	-	6,045	12.28	16.30
DDCV	95,525	120,701	17.91	0.09	16.97	0.00	29,299	54,475	12.62	13.84
SDVAV	66,296	84,491	15.80	0.11	14.75	0.00	66,296	84,491	0.86	0.86
CVRH		150,000	15.58	0.06	15.02	0.00		150,000	8.83	8.83

Table 6. Ton hr/cfm for Annual Cooling & Heating Loads (10% & 40% Ventilation Air) for Phoenix

	COOLING						HEATING			
SYSTEM	Flow Range		10%		40%		Flow Range		10%	40%
	minimum	maximum	Sens	Lat	Sens	Lat	minimum	maximum	Sens	Sens
	cfm		ton hr/cfm				cfm		ton hr/cfm	
DDVAV	55,622	77,546	11.81	0.98	5.32	2.62	-	10,675	29.33	36.17
DDCV	95,525	120,701	16.09	0.64	9.87	1.54	29,299	54,475	25.83	32.94
SDVAV	66,296	77,546	11.81	0.97	5.32	2.62	66,296	77,546	2.70	2.70
CVRH		150,000	13.77	0.45	8.10	1.22		150,000	9.95	9.95

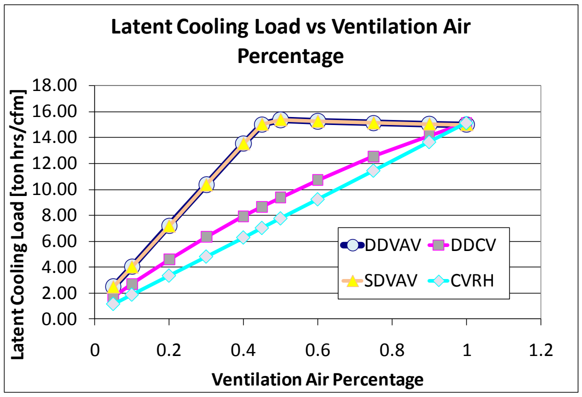

Figure 14. Latent Cooling Load vs Ventilation Air Percentage

CONCLUSIONS

The Ventilation Load Index analysis shows evidence that joint-frequency bin weather data produces more accurate results than conventional temperature or humidity bins. On the system performance analysis level, when the ventilation air is in the normal range of 10-15%, conventional bins provide very similar results to joint-frequency bins in all climate regions with percent differences less than 3%. The percent differences increase with increased ventilation air, with the magnitude of increase varying by climatic region. For 40% ventilation air, the lowest increase was in Houston, a hot and humid climate, with % differences less than 2%; however the greatest increase was prevalent in Phoenix with % differences around 10%. From this study the use of joint-frequency bins appear to have moderate added value to the analysis of HVAC system operation depending on the ventilation loads present in the system. Important factors to consider when choosing which type of bin data to use include the effect of ventilation air on the analysis, the desired level of accuracy and the climatic region.

REFERENCES

Claridge, D. E. 2007. MEEN 664 Energy Management in Commercial Buildings *Lecture notes*. Department of Mechanical Engineering. Texas A&M University. College Station, TX.

Cohen, B. M., D. Kosar. 2000. "Humidity Issues in Bin Energy Analysis." Heating/Piping/Air Conditioning Engineering: HPAC. Jan. 72, 1. ABI/INFORM Trade & Industry. Pg. 65.

Harriman, L.G., D. Plager, and D. Kosar. 1997. "Dehumidification and cooling loads from ventilation air. ASHRAE Journal." Nov. pp 37-45.

Jones, A, J.C. Baltazar. 2009. "BINTOOL: For Energy Analysis." Energy Systems Laboratory. Texas A&M University System.

Microsoft® Encarta® Online Encyclopedia. 2009. "United States Geography." http://encarta.msn.com © 1997-2009 Microsoft Corporation.

National Renewable Energy Laboratory. 2009. Typical meteorological years derived from the 1961-1990 National Solar Radiation Database. http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/.