PNNL-20026

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Energy Saving Impact of ASHRAE 90.1 Vestibule Requirements:

Modeling of Air Infiltration through Door Openings

H Cho
B Liu
K Gowri

November 2010

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

**Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov**

**Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm**

This document was printed on recycled paper.
(9/2003)

PNNL-20026

Energy Saving Impact of ASHRAE 90.1 Vestibule Requirements:

Modeling of Air Infiltration through Door Openings

H Cho K Gowri
B Liu

November 2010

Prepared for
U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

This report presents a methodology for modeling air infiltration through door openings. This report shows that the estimation of air infiltration rate using the proposed method can be readily used in EnergyPlus whole building energy simulations. The purpose of this study is two-fold:

1. Develop a modeling strategy to capture the energy saving impacts of ASHRAE 90.1 vestibule requirements (i.e., addendum ‘c’ to ASHRAE Standard 90.1-2004 and addendum ‘q’ to ASHRAE Standard 90.1-2007).
2. Provide a guideline to model air infiltration through door openings calculated for the whole building simulations to determine its impact for various types of buildings.

Pacific Northwest National Laboratory’s (PNNL) prototypical commercial building models were used in the analysis to determine energy savings from the vestibule requirements. The national construction-weighted average savings for each building prototype from ASHRAE 90.1 vestibule requirements have been determined, and the results are presented in the table below.

Table S 1. National weighted-average savings for each building prototype

Building Type	Savings (%)	Building Type	Savings (%)
Small Office	0.63	Secondary School	0.06
Medium Office	0.23	Quick Service Restaurant	4.16
Warehouse	0.36	Sit-down Restaurant	1.89
Stand-alone Retail	2.38	Outpatient Health Care	0.03
Strip Mall	5.61	Small Hotel	0.57
Primary School	0.29	Mid-rise Apartment	0.30

Contents

Figures

Tables

1. Introduction

Saving energy in residential and commercial buildings is considered to be a key area to achieve significant energy saving nationwide[1]. Because saving energy in the building sector is a vital issue, the importance of energy smart "whole building" design and analysis is also emphasized [1, 2]. Many factors need to be considered in a whole building analysis to realistically evaluate building energy savings; one of the important factors is air infiltration through the building envelope [3]. Along with whole building air leakage, air infiltration through door openings can be an important factor when doors are used frequently. Many commercial buildings, such as restaurants, strip-mall stores, retail stores, supermarkets, offices and hospitals, are likely to have high door-opening frequency, either at certain time periods of day or in some cases throughout the occupied hours. Vestibules or revolving doors are often considered as design measures to decrease the air infiltration through door openings and ultimately to reduce the whole building energy use when doors are used frequently. To this effect, commercial building energy codes such as ASHRAE Standard 90.1 require installing vestibules in some situations. Addendum 'c' to ASHRAE Standard 90.1-2004 and addendum 'q' to ASHRAE Standard 90.1-2007 were developed by the ASHRAE 90.1 Envelope Subcommittee to require vestibules in some buildings and in certain climate zones to reduce air infiltration through building entrance doors.

Whole building energy simulation tools can be effectively used to determine the energy impact caused by air infiltration through building door openings, and the energy savings potential for reducing that infiltration. A few studies have been conducted to estimate air infiltration rates of automatic doors for different type of buildings [4, 5]. However, to the authors' knowledge, no published study was found to estimate the energy saving impact of infiltration rate through the door openings. A method to estimate air infiltration rate through the door openings with and without vestibules is presented in this report. Peak infiltration rates through door openings for each building type, with and without vestibules, were estimated, and the estimated values were then directly used in EnergyPlus building energy simulation to estimate the impact of specific vestibule requirements introduced into ASHRAE 90.1 on building energy use.

[1] The U.S. Department of Energy reported that the building sector consume approximately 40% of U.S. primary energy annually [1].

The primary objectives of this study are to:

1. Develop a modeling strategy to capture the energy saving impacts of ASHRAE 90.1 vestibule requirements (i.e., addendum ‘c’ to ASHRAE Standard 90.1-2004 and addendum ‘q’ to ASHRAE Standard 90.1-2007[2]).
2. Provide a guideline of how to model air infiltration through the door openings in the whole building simulations to determine its impact for various type of buildings.

In the analysis, exterior doors in each prototype are assumed to be automatic doors. The main reason for this simplifying assumption is that door opening pattern of manual doors is extremely difficult (i.e., depending on users’ pattern, the door opening area and opening time can vary significantly). However, methods to estimate air flow through automatic doors are available in the literatures [4-6]. Because automatic doors often stay open longer with each use than manual doors, this assumption may result in over-estimates of infiltration rates through door-openings for buildings that more typically use manual doors.

---

[2] Addendum ‘c’ to ASHRAE Standard 90.1-2004 and addendum ‘q’ to ASHRAE Standard 90.1-2007 are provided in Appendix A.

2. Modeling Strategy for Air Infiltration through Door Openings

Air infiltration through door openings can be determined based on the type and usage of buildings and on outdoor wind speed and building pressure differentials. Because of the constant variation in wind speed and pressure and door usage, actual air infiltration through doors can vary greatly over the year. However, for this study, the air flow rates through open doors are assumed to be constant and were based on design/typical values available in the literature. Because air flow through a door for each door opening is assumed to be constant in this analysis, the number of people using a door per hour is identified as a key parameter to estimate air flow through doors in different types of buildings. The pressure difference across a door in a building is the driving force in the actual air flow calculation for the time the door is open. This pressure difference depends on pressure difference caused by stack effect and wind-induced surface pressure to static pressure. ASHRAE design values [6] for the square root of the pressure difference across the door have been recommended for use in the door-air flow calculation.

Following the method introduced in the ASHRAE handbook [6], the infiltration rate through the automatic door can be determined by

$$Q = C_A A R_p$$

where,

Q is air flow rate (cfm),

C_A is air flow coefficient (cfm/ft^2-(in. of water)$^{0.5}$),

A is area of the door opening (ft^2), and

R_p is a pressure factor (in. of water$^{0.5}$).

The air flow coefficient C_A with and without vestibules, as shown in Figure 1, can be expressed as a function of the door-opening frequency (i.e., the number of people using a door per hour). Note that Figure 1 was developed by ASHRAE research project RP-763 [4] to simplify the air flow calculation through automatic doors with the following assumptions: (a) the wind velocity on the design day is assumed to be at 15 mph; (b) the neutral pressure plane is assumed to be at the mid-height of the building; and (c) the draft coefficient in the building is 0.9. Under these assumptions, the pressure factor R_p is a design value, which serves to represent the effect of a design pressure difference across the door, and it can be obtained using Figure 2. This value remains the same for vestibules.

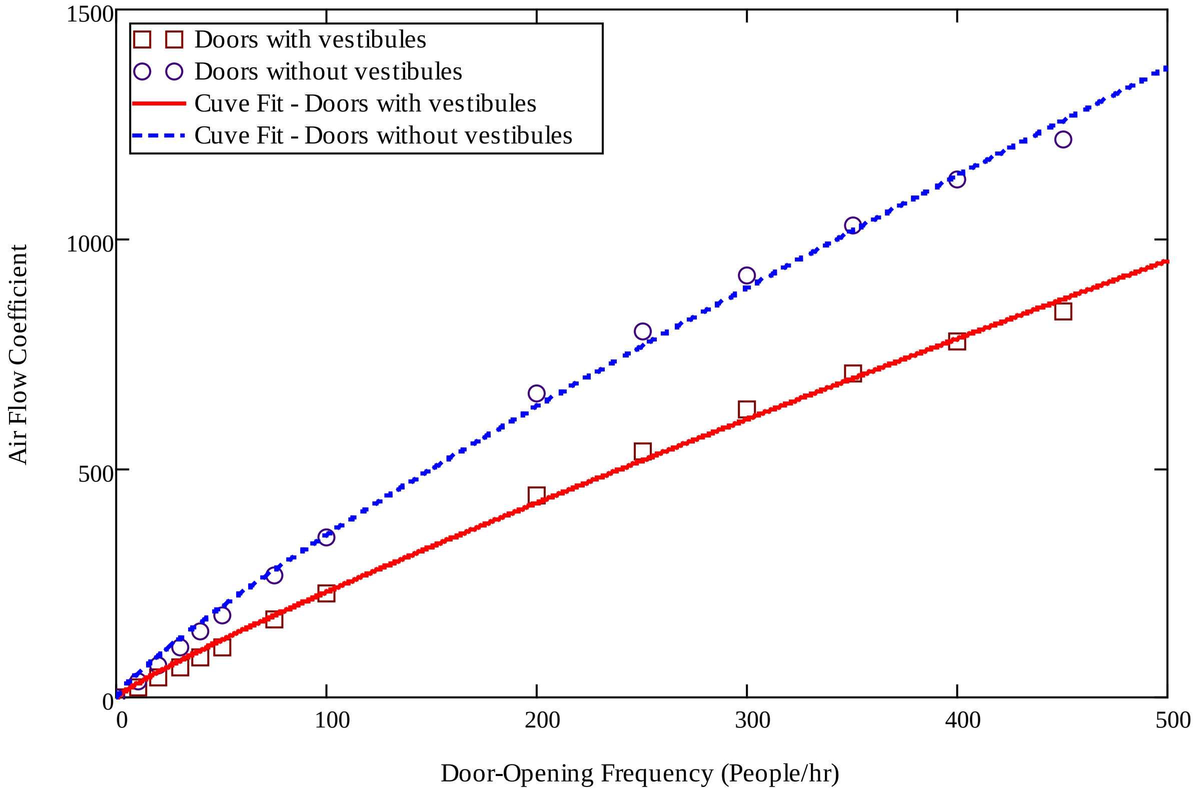

Figure 1: Air flow coefficient vs. door-opening frequency [4]

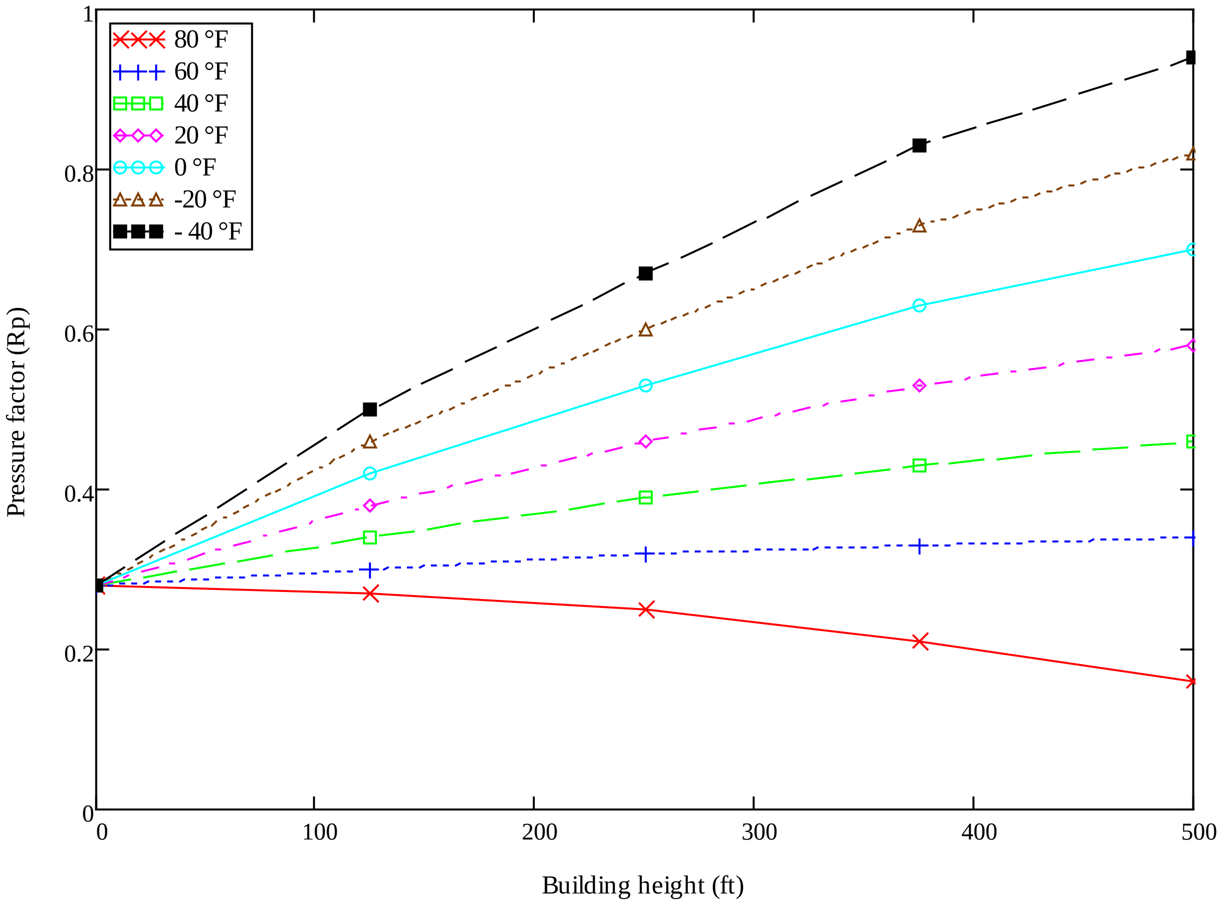

Figure 2: Pressure factor vs. building height at different outdoor air temperatures [4]

3. Building Models and ASHRAE 90.1 Vestibule Requirements

PNNL's commercial prototypical building models[3] were used in this study to determine the energy saving impact from ASHRAE 90.1 vestibule requirements. The starting point for these models follows the minimum requirements of Standard 90.1-2004. Each building prototype was analyzed for the vestibule requirements in ASHRAE 90.1-2004 and under subsequent standard modifications. The characteristics of each building model are described in Table 1, and this information is used to determine vestibule requirements for each building type. The ASHRAE 90.1 vestibule requirement found in the 2004 standard, 2007 standard (addendum 'c' to 90.1-2004) and addendum 'q' to 90.1-2007 are described in Appendix A.

Table 1 Prototype model characteristics to determine vestibule requirements

Building Prototype	Gross Floor Area [ft^2]	Number of stories	Floor Footprint Area [ft^2]	Entrance Zone Area* [ft^2]	Building Height [ft]
Large Office	498,600	12	38,400	3,373	156
Medium Office	54,000	3	17,876	2,232	39
Small Office	5,500	1	5,500	1,221	10
Warehouse	49,500	1	49,500	2,550	28
Quick Service Restaurant	2,500	1	2,500	1,250	10
Sit-down Restaurant	5,500	1	5,500	4,002	10
Strip Mall	22,500	1	22,500	3,750/1,875	17
Stand-alone Retail	24,695	1	24,695	17,227	20
Primary School	73,960	1	73,960	1,840	13
Secondary School	210,900	2	128,242	2,260	26
Small Hotel	43,200	4	10,800	1,755	38
Large Hotel	122,130	6	21,300	14,081	71
Hospital	241,410	5	40,250	15,875	78
Outpatient Health Care	40,950	3	13,650	1096	30
High-rise Apartment	84,360	10	8,436	836	100
Mid-rise Apartment	33,700	4	8,436	836	40

* Entrance zone area is a conditioned space where the entrance doors are located and is modeled as a "conditioned/semi-conditioned" zone in the building.

---

[3] PNNL's prototypical building models are closely related to DOE's commercial reference building series [7]. The Department of Energy's (DOE) Building Technologies Program, working with DOE's three national laboratories [including National Renewable Energy Laboratory (NREL), PNNL, and Lawrence Berkeley National Laboratory (LBNL)] developed reference models for 16 commercial building types in 16 locations representing all U.S. climate zones. Several prototypical building descriptions can be found in PNNL reports [8-10].

In Tables 2, 3 and 4, all the prototypes in each climate zone are identified for the vestibule requirement for each standard and addendum. Tables 2, 3 and 4 show that the vestibule requirements in 90.1-2004, 90.1-2007 and addendum ‘q’ are the same for large office, large hotel, high-rise apartment and hospital. Because vestibules are always required, these buildings are assumed to have no savings from vestibule requirements examined in this study. No further analysis to estimate savings has been performed for large office, large hotel, high-rise apartment and hospital in this study.

Table 2 ASHRAE 90.1 - 2004 vestibule requirement for all prototypes in each zone

Building Prototype	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Large Office	No (a)	No (a)	Yes	Yes	Yes	Yes	Yes	Yes
Medium Office (b),(e)	No (a)	No (a)	No	No	No	No	No	No
Small Office (b),(e)	No (a)	No (a)	No	No	No	No	No	No
Warehouse (b),(e)	No (a)	No (a)	No	No	No	No	No	No
Quick Service Restaurant (b),(e)	No (a)	No (a)	No	No	No	No	No	No
Sit-down Restaurant (b)	No (a)	No (a)	No	No	No	No	No	No
Strip Mall (b)	No (a)	No (a)	No	No	No	No	No	No
Standalone Retail (b)	No (a)	No (a)	No	No	No	No	No	No
Primary School (b),(e)	No (a)	No (a)	No	No	No	No	No	No
Secondary School (b),(e)	No (a)	No (a)	No	No	No	No	No	No
Small Hotel (e)	No (a)	No (a)	No	No	No	No	No	No
Large Hotel	No (a)	No (a)	Yes	Yes	Yes	Yes	Yes	Yes
Hospital	No (a)	No (a)	Yes	Yes	Yes	Yes	Yes	Yes
Outpatient Health Care (b)	No (a)	No (a)	No	No	No	No	No	No
High-rise Apartment (e)	No (a)	No (a)	Yes	Yes	Yes	Yes	Yes	Yes
Mid-rise Apartment (e)	No (a)	No (a)	No	No	No	No	No	No

Note: 90.1 exceptions, which are used in determining that no vestibule requirement exists for a building in a particular climate zone, are shown in parenthesis (See Appendix A for the description of exceptions)

Table 3 ASHRAE 90.1 - 2007 vestibule requirement for all prototypes in each zone (Addendum ‘c’ to 90.1-2004)

Building Prototype	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Large Office	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Medium Office	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Small Office	No (d)	No (d)	No (e)	No (e)	Yes	Yes	Yes	Yes
Warehouse	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Quick Service Restaurant	No (d)	No (d)	No (e)	No (e)	Yes	Yes	Yes	Yes
Sit-down Restaurant	No (d)	No (d)	No (e)	No (e)	Yes	Yes	Yes	Yes
Strip Mall	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Standalone Retail	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Primary School	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Secondary School	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Small Hotel	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Large Hotel	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Hospital	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Outpatient Health Care	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
High-rise Apartment	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Mid-rise Apartment	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes

Note: 90.1 exceptions, which are used in determining that no vestibule requirement exists for a building in a particular climate zone, are shown in parenthesis (See Appendix A for the description of exceptions)

Table 4 Addendum ‘q’ to ASHRAE 90.1 - 2007 vestibule requirement for all prototypes in each zone

Building Prototype	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Large Office	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Medium Office	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Small Office	No (d)	No (d)	No (e)	No (e)	Yes	Yes	Yes	Yes
Warehouse	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Quick Service Restaurant	No (d)	No (d)	No (e)	No (e)	Yes	Yes	Yes	Yes
Sit-down Restaurant	No (d)	No (d)	No (e)	No (e)	Yes	Yes	Yes	Yes
Strip Mall	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Standalone Retail	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Primary School	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Secondary School	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Small Hotel	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Large Hotel	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Hospital	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Outpatient Health Care	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
High-rise Apartment	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes
Mid-rise Apartment	No (d)	No (d)	Yes	Yes	Yes	Yes	Yes	Yes

Note: 90.1 exceptions, which are used in determining that no vestibule requirement exists for a building in a particular climate zone, are shown in parenthesis (See Appendix A for the description of exceptions)

4. Estimation of Door-Opening Frequency

Estimating reasonable values of door-opening frequency for different types of buildings is important to calculate the infiltration rate through doors. Door-opening frequency can be determined by field observations, but it is costly and time-consuming work. It can also be determined by estimating occupancy information in buildings. In the analysis, door-opening field data was used for some prototype buildings if the data is available in the literature. Otherwise, the number of occupants and the occupancy schedule in each prototype building is used to estimate a corresponding door-opening frequency. The door-opening frequency for each building prototype at peak hour is shown in Table 5. The door-opening frequencies for off-peak-hours were estimated at one-tenth of the value during the peak-hour for all prototypes and are also shown in Table 5. The detailed method to estimate the building occupancy for each prototype is described in the following sub-sections.

Table 5 Door-opening frequency estimation for each building type[4]

Building Type	Peak occupancy [persons]	Door-opening frequency [number of door openings per hour]	
		Peak	Off-peak
Small Office	9	9	1
Medium Office	105	105	10
Warehouse	23	23	2
Standalone Retail	77	153	15
Strip Mall (large store/small store)	17/8	34/16	3/2
Primary School	580	580	58
Secondary School	1041	1041	104
Quick Service Restaurant	90	90	9
Sit-down Restaurant	57	57	6
Outpatient Health Care	123	123	12
Small Hotel	90	90	9
Mid-rise Apartment	46	46	5

[4] The door-opening frequency for peak hour can be estimated based on the number of occupants in a building. For retail and strip mall stores, it is assumed that customers would use entrance door two times within 1 hour (i.e., once they enter and once they leave the store). However, for other building types it can be safely assumed that people stay longer than 1 hour in the building and use the entrance door once within 1 hour when they enter or leave. Therefore, the door-opening frequency for peak hour can be estimated to be equal to the number of occupants in all prototypical buildings except retail and strip mall stores.

Small Office, Medium Office and Warehouse

The number of occupants (workers) for small office, medium office and warehouse is estimated based on the occupancy survey data collected in the Commercial Buildings Energy Consumption Survey (CBECS) by Energy Information Administration (EIA) [12]. From the 2003 CBECS data, the number of workers for small office, medium office and warehouse prototype was determined to be 9, 105, and 5, respectively.

Quick Service and Sit-Down Restaurants

The number of customers for quick service and sit-down restaurant prototype buildings was determined using data from a field study conducted by Claar et al. [13]. The average daily number of customers was reported as 898 for a quick service restaurant and 284 for a sit-down restaurant. It is assumed that a half of customers for a quick service restaurant use drive-through. If we assume that the customer comings and goings are evenly distributed over 5 hours of peak time building usage, the number of customers can be estimated as 90 (= 898/2/5) for the quick service restaurant model and 57 (=284/5) for the sit-down restaurant model.

Standalone Retail and Strip Mall

The average door-opening frequency for standalone retail stores is directly obtained from the field observation data collected by Yuill [4]. The total number of 52 data sets was collected in different locations. The averaged peak door-opening frequency is then calculated to be 153 (opening/hour). If it is assumed that customers do not normally stay longer than 1 hour in the retail and strip mall stores, each customer would use the entrance door two times within 1 hour. Therefore, the number of people in the store during peak hours can be estimated to be one-half of the average door-opening frequency. Then the number of people in the store during peak hours is estimated to be 77. The strip mall prototype is assumed to have the same number of people (N_{retail}) per entrance zone area (A_{retail}). The entrance zone area of the standalone retail prototype (A_{retail}) is 17,227 ft^2 (see Table 1). Then the area occupied per person (O_{retail}) for the retail prototype is determined as

$$O_{retail} = A_{retail} / N_{retail} = 223.7 \text{ ft}^2$$

In the strip mall prototype, there are two different sizes of stores within the prototype building: two stores with 3,750 ft^2 and eight stores with 1,875 ft^2. There are multiple stores of each size. The number of occupants of the strip mall prototype (N_{strip}) for each zone size can be estimated as

$$\text{Large store: } N_{strip} = 3{,}750 \text{ ft}^2 / O_{retail} \approx 17$$

$$\text{Small store: } N_{strip} = 1{,}875 \text{ ft}^2 / O_{retail} \approx 8$$

Then, the peak door-opening frequency for large stores and small stores can be estimated to be 34 and 16 (opening/hour), respectively.

Primary and Secondary Schools

The total number of occupants in schools consists of the number of staff including teachers and the number of students. The number of staff for primary school and secondary school are estimated to be 64 and 115, respectively, from the CBECS data [12]. The number of students is estimated based on the national averages of teacher-to-staff ratio (R_{t2sf}) and student-to-teacher ratio (R_{s2t}):

$$\text{Number of teachers} = \text{Number of staff} \times R_{t2sf}$$

$$\text{Number of students} = \text{Number of teachers} \times R_{s2t}$$

where the national average of teacher-to-staff ratio is 0.512 in 2005 [14] and the national average of student-to-teacher ratio is 15.7 in 2005 [15]. The total number of occupants is the sum of the number of students and staff. The total number of occupants was estimated to be 580 for the primary school prototype and 1041 for the secondary school prototype.

Outpatient Health Care

The average door opening frequency for outpatient health care is directly obtained from the field observation data collected by Yuill [6]. A total number of 16 data sets were collected in different locations. The average door-opening frequency is calculated to be 123 (opening/hour). This value is used for the peak hour door-opening frequency.

Small Hotel and Mid-rise Apartment

For small hotel and mid-rise apartment prototypes, the number of rooms/units is used to estimate the number of occupants. In the small hotel prototype, 77 rooms are available for customers. According to the 2007 Lodging Industry Profile report [16], the average occupancy rate was 63.3% for the lodging industry in 2006, and there is usually one person in a business room and two persons in a leisure room. Based on this information, it is assumed that 65% of guest rooms are occupied and 1.5 people stay in each rented room. From the CBECS data [12], the average number of workers in small hotels is given by 15.

Then the total occupancy in the small hotel prototype was determined as 90 ($\approx 77 \times 0.65 \times 1.5 + 15$). There are 23 apartment units available for residence in the mid-rise apartment prototype. It was assumed that two people live in each apartment on average, resulting in the total number of residents to be estimated as 46 for the mid-rise apartment.

5. Estimation of Air Infiltration through Door Openings

Using the method described in Section 2 and the door-opening frequency information in Section 4, the air infiltration rates through door openings for each prototype are estimated in this section. In this estimation, the outdoor temperature is assumed to be 60°F, and the door opening area is assumed to be 21 ft^2 (= 7 ft × 3 ft). The estimated values with and without vestibules are presented in Table 6. A sensitivity analysis, discussed in Section 7, shows that variation in the outdoor temperature for low-rise buildings has a relatively small contribution to the total introduced infiltration compared to the variation in door-opening frequency. The buildings heights for those that are the subject to the new ASHRAE 90.1-2007 and subsequent addenda vestibule requirements are less than or equal to 40 ft, as described in Table 1. This means that the variation in outdoor temperature results in relatively small changes in the air infiltration rate through door openings (i.e., as shown in Figure 2, the pressure factor (Rp) will have very small changes as varying outdoor temperature from -40°F to 80°F for the building height lower than or equal to 40 ft). Therefore, a fixed outdoor temperature assumption for establishing the infiltration rate through the door appears to be a reasonable assumption for this type of analysis.

Table 6 Air infiltration rates through door openings with and without vestibule

Building Type	Air infiltration rate [cfm] through doors with vestibule		Air infiltration rate [cfm] through doors without vestibule	
	Peak	Off-peak	Peak	Off-peak
Small Office	162	21	275	40
Medium Office	1,438	188	2,210	318
Warehouse	374	49	612	88
Standalone Retail	1,986	260	3,006	432
Strip Mall (large store/small store)	511/285	67/37	824/471	118/68
Primary School	6,423	840	9,205	1,323
Secondary School	10,837	1,417	15,161	2,179
Quick Service Restaurant	1,237	162	1,913	275
Sit-down Restaurant	826	108	1,302	187
Outpatient Health Care	1,646	215	2,513	361
Small Hotel	1,254	164	1,940	279
Mid-rise Apartment	694	91	1,103	159

In Table 7, the door-opening schedule for each prototype is estimated based on the occupancy schedule in the building models. Note that the cells highlighted in yellow indicate the off-peak hours, while the cells highlighted in green indicate the peak hours. For buildings other than restaurants, the off peak hours have one-tenth the door operation as at peak hour. For the restaurants, however, fractional values of the peak hour door-opening frequency used in the simulation are presented in Table 7. Fractional schedules (i.e., smooth transition between the hours) were considered in the restaurant models to remove the unexpected simulation results (e.g., sudden increase of heating, ventilation, and air conditioning (HVAC) system energy use from off-peak hour to peak hour). The values in Tables 6 and 7 can be readily used in the EnergyPlus to model the air infiltration through door opening with and without vestibule, and it can be modeled as direct air flow to an entrance zone.

Table 7 Door-opening schedule for each building type

		12-6a	6-7a	7-8a	8-9a	9-10a	10-11a	11a-12p	12-1p	1-2p	2-3p	3-4p	4-5p	5-6p	6-7p	7-8p	8-9p	9-10p	10-11p	11-12a
Small Office	Week Day																			
	Weekend																			
Medium Office	Week Day																			
	Weekend																			
Warehouse	Week Day																			
	Weekend																			
Standalone Retail	All																			
Strip Mall	All																			
Primary School	Week Day																			
	Weekend																			
Secondary School	Week Day																			
	Weekend																			
Quick Service Restaurant	Week Day		0.144	0.462	0.462	0.462	0.258	0.558	0.829	0.74	0.462	0.258	0.363	0.558	0.829	0.829	0.829	0.558	0.363	0.258
	Weekend		0.144	0.558	0.558	0.462	0.258	0.462	0.558	0.558	0.462	0.363	0.363	0.363	0.74	0.915	0.74	0.65	0.558	0.363
Sit-down Restaurant	Week Day		0.144	0.462	0.462	0.462	0.258	0.558	0.829	0.74	0.462	0.258	0.363	0.558	0.829	0.829	0.829	0.558	0.363	0.258
	Weekend		0.144	0.558	0.558	0.462	0.258	0.462	0.558	0.558	0.462	0.363	0.363	0.363	0.74	0.915	0.74	0.65	0.558	0.363
Outpatient Health Care	Week Day																			
	Weekend																			
Small Hotel	All																			
Mid-rise Apartment	All																			

Peak hour | Off-peak hour | Unoccupied/no door usage

6. Simulation Results

EnergyPlus simulations were performed to estimate energy saving impacts from ASHRAE 90.1 vestibule requirements. Air infiltration rates through door openings with and without vestibule and door-opening schedules were implemented in EnergyPlus building models as zone infiltration rates to entrance zones. From the whole building simulations, energy end uses for all prototypical buildings and all climate zones that are subjected to ASHRAE 90.1 vestibule requirements are estimated. The national weighted-average savings for each building prototype from ASHRAE 90.1 vestibule requirements are presented in Table 8.

Table 8 National weighted-average site energy savings for each building prototype

Building Type	Energy End Use Savings [kBtu/ft^2]	Savings [%]
Small Office	0.13	0.63
Medium Office	0.09	0.23
Warehouse	0.09	0.36
Standalone Retail	1.49	2.38
Strip Mall	3.56	5.61
Primary School	0.16	0.29
Secondary School	0.04	0.06
Quick Service Restaurant	13.3	4.16
Sit-down Restaurant	4.56	1.89
Outpatient Health Care	0.04	0.03
Small Hotel	0.34	0.57
Mid-rise Apartment	0.11	0.30

* The weighting factors used to calculate national average savings are different for each building and each climate zone. In the calculation, the energy savings were assumed to be zero for those climate zones where are not subject to the new ASHRAE 90.1-2007 and subsequent addenda vestibule requirements (see Tables 3 and 4), and this was reflected in the saving calculations and in Figures 3 through 14. The weighting factors, as well as the method to estimate the weighting factors and their values can be found in PNNL reports [10, 11].

It is expected that smaller buildings with high door-opening frequency would tend to have larger percentage reduction savings from vestibules. From the results shown in Table 8, the following can be observed:

- Although strip mall, standalone retail, quick service restaurant, and sit-down restaurant building have much smaller peak air infiltration rates through door openings compared to other type of buildings, those buildings have greater percentage energy savings because of the building size and door-opening frequency/schedule.

- Small office has larger percentage savings compared to medium office because it has smaller total floor area that can be impacted greatly by air infiltration through door openings. The same fact can be examined between primary and secondary schools.
- Larger buildings tend to have smaller impact regarding whole building energy use by air infiltration through door openings compared to the smaller buildings, but the absolute savings are much larger as expected.
- Even though primary and secondary school buildings have very frequent door openings with resultant large amounts of air infiltration rate through door opening at peak hours, the overall percentage energy savings impact of the vestibule addenda air leakage through the door is fairly small. This is caused by larger floor area resulting high baseline energy use.

Figures 3 through 14 show the energy saving results for each prototypical building and each climate zone. It is observed from these figures that in general, larger percentage energy savings from the vestibule requirement is expected in the colder climate zones. Although the same infiltration rate through doors/vestibules was used for each building type across climates, the impact in terms of vestibule benefits depends on the outdoor air temperature and humidity conditions.

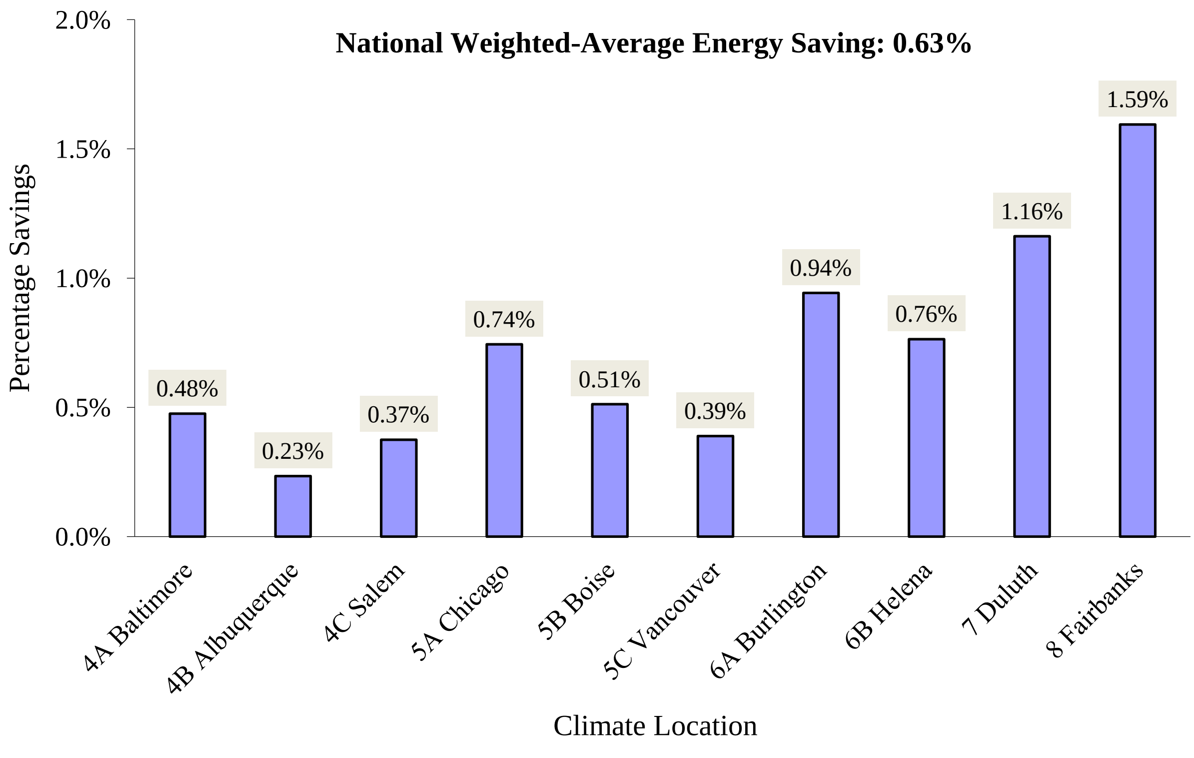

Figure 3: Percentage energy savings from ASHRAE 90.1 vestibule requirements for small office building prototype

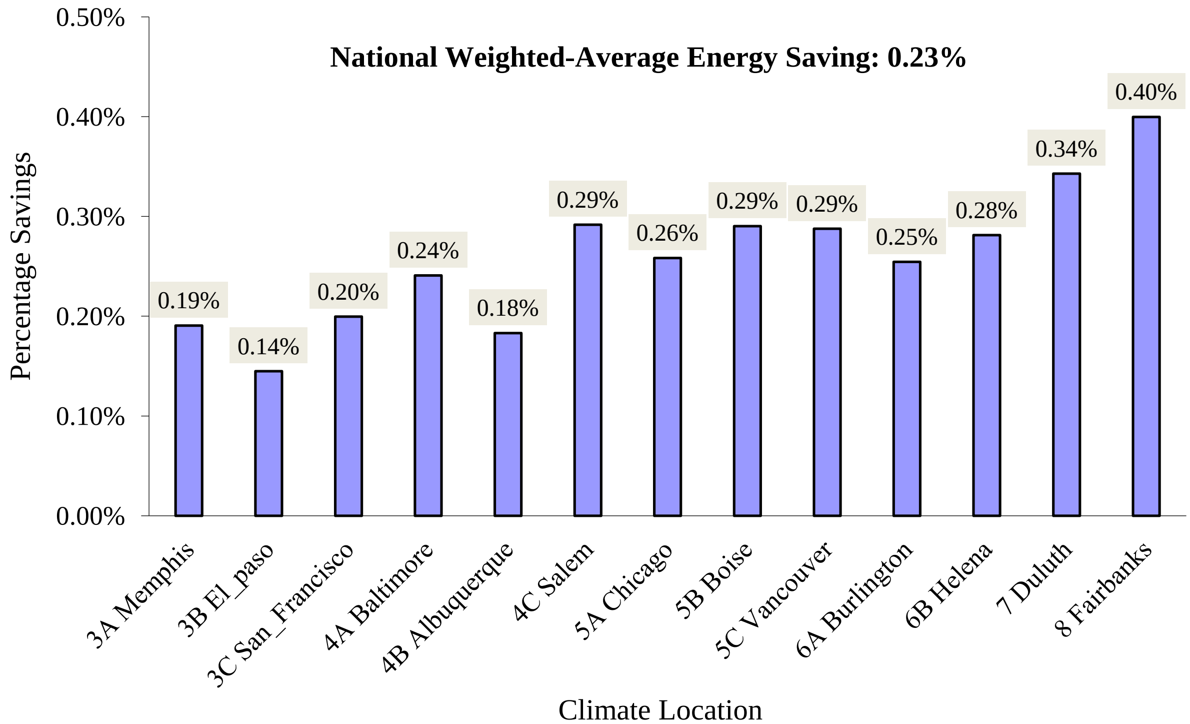

Figure 4: Percentage energy savings from ASHRAE 90.1 vestibule requirements for medium office building prototype

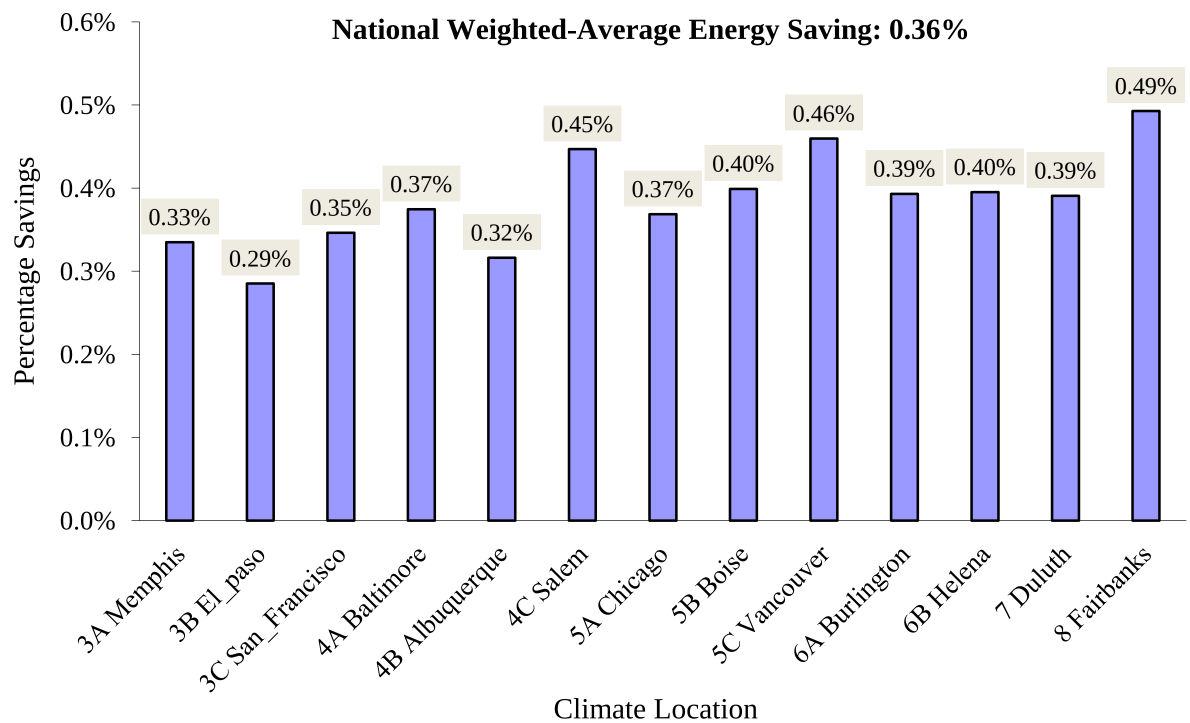

Figure 5: Percentage energy savings from ASHRAE 90.1 vestibule requirements for warehouse building prototype

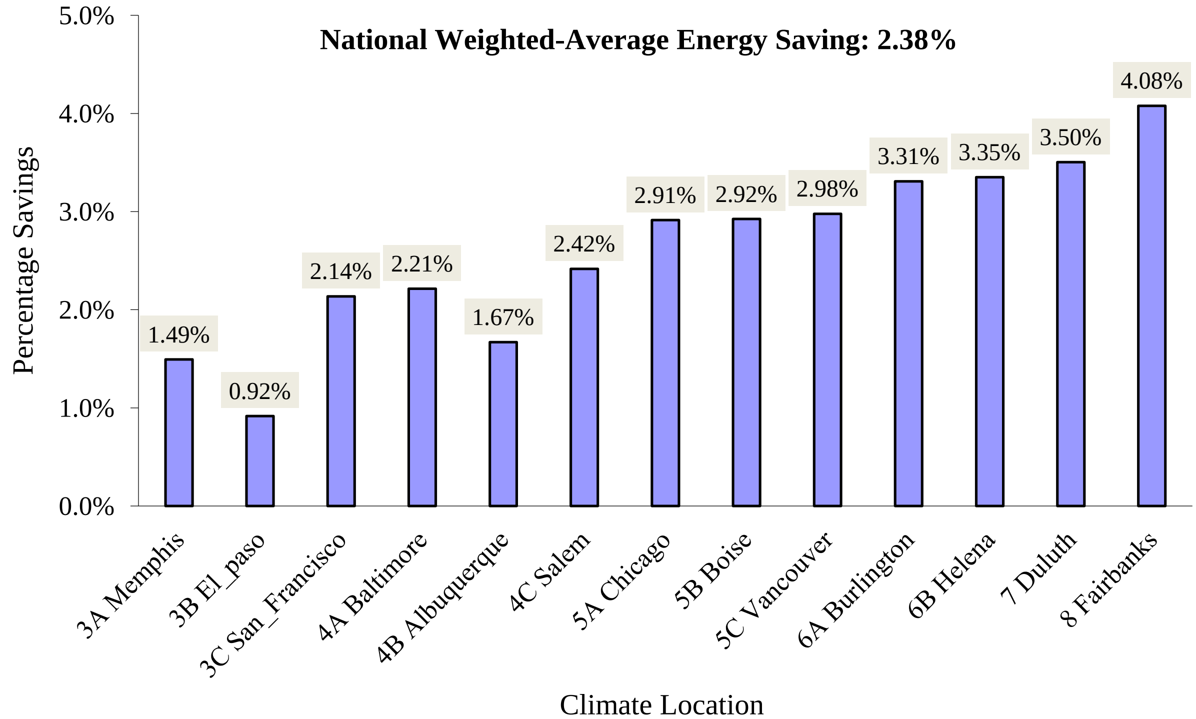

Figure 6: Percentage energy savings from ASHRAE 90.1 vestibule requirements for standalone retail building prototype

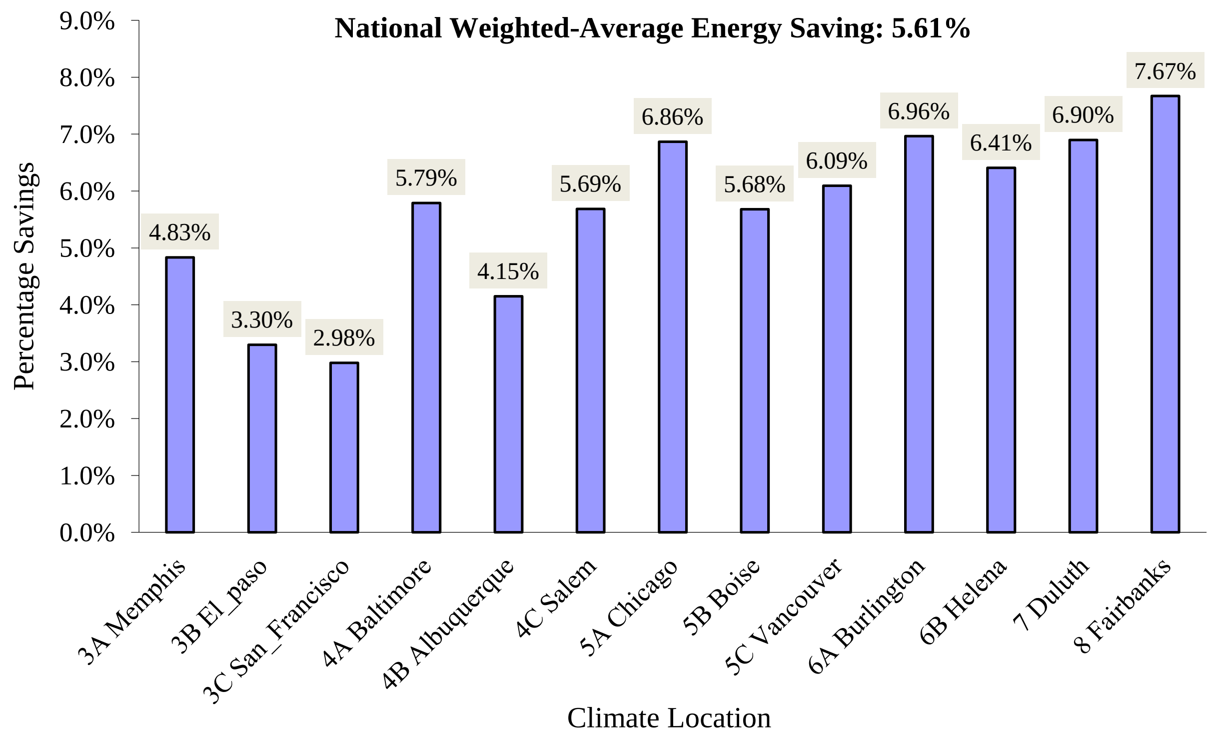

Figure 7: Percentage energy savings from ASHRAE 90.1 vestibule requirements for strip mall building prototype

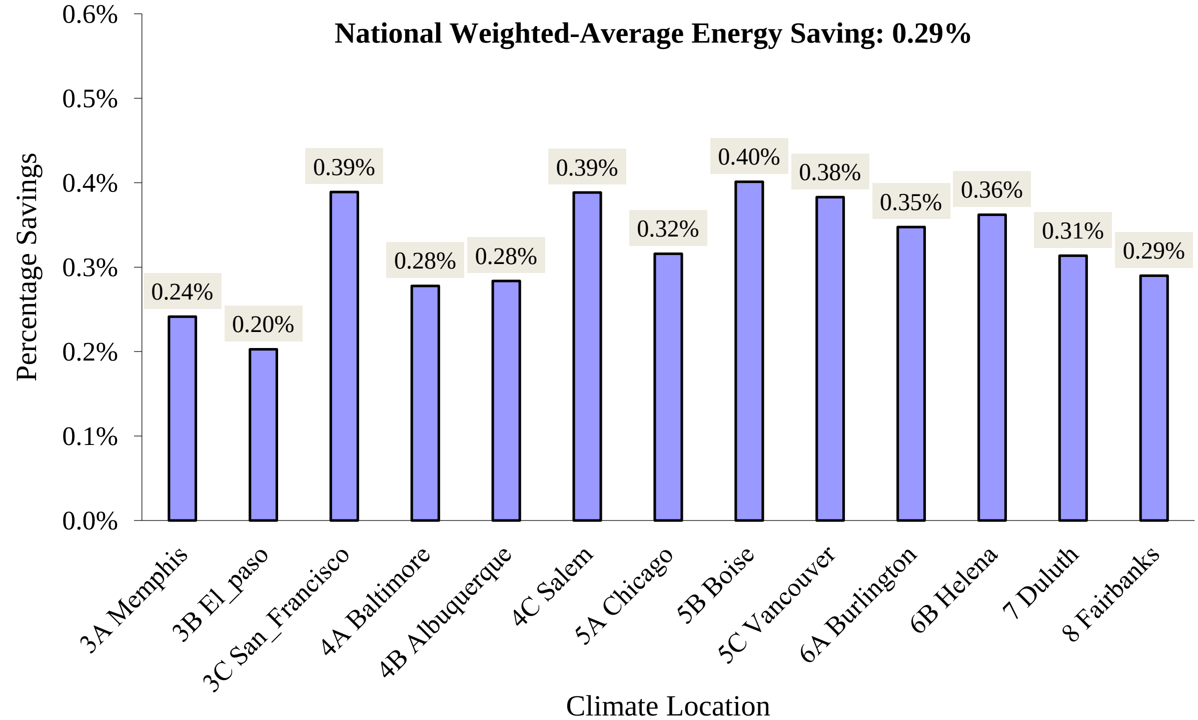

Figure 8: Percentage energy savings from ASHRAE 90.1 vestibule requirements for primary school building prototype

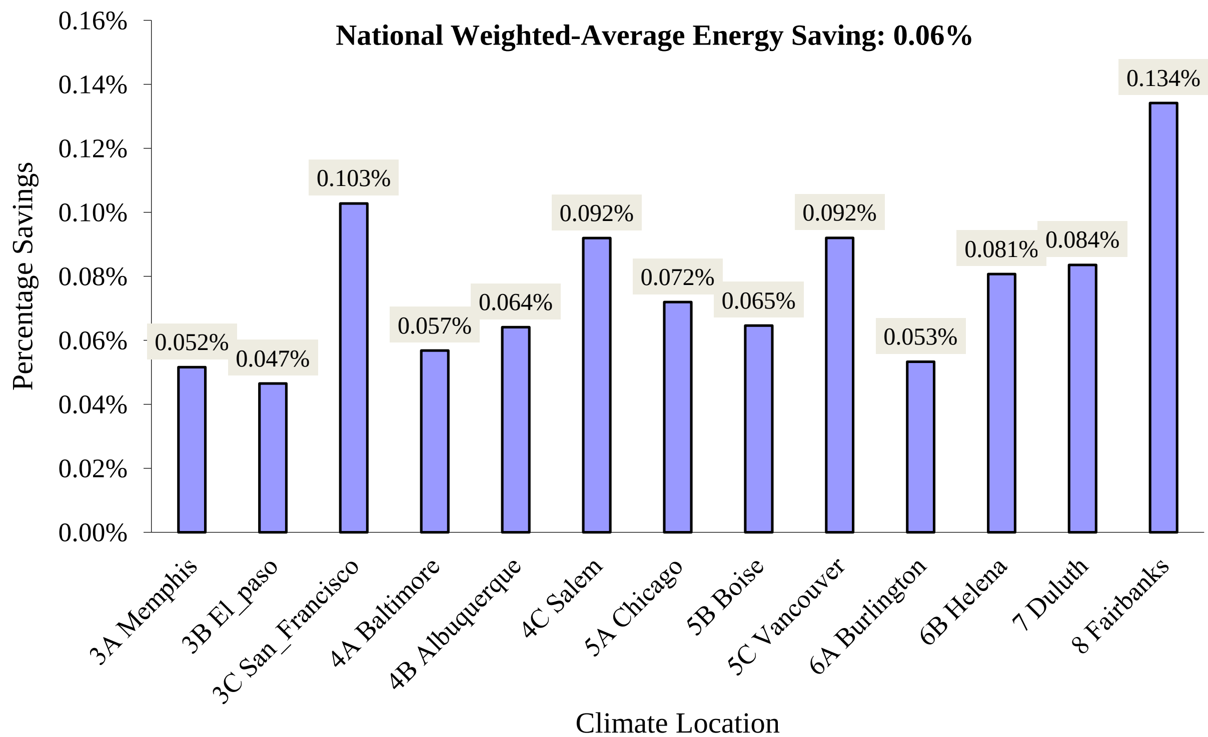

Figure 9: Percentage energy savings from ASHRAE 90.1 vestibule requirements for secondary school building prototype

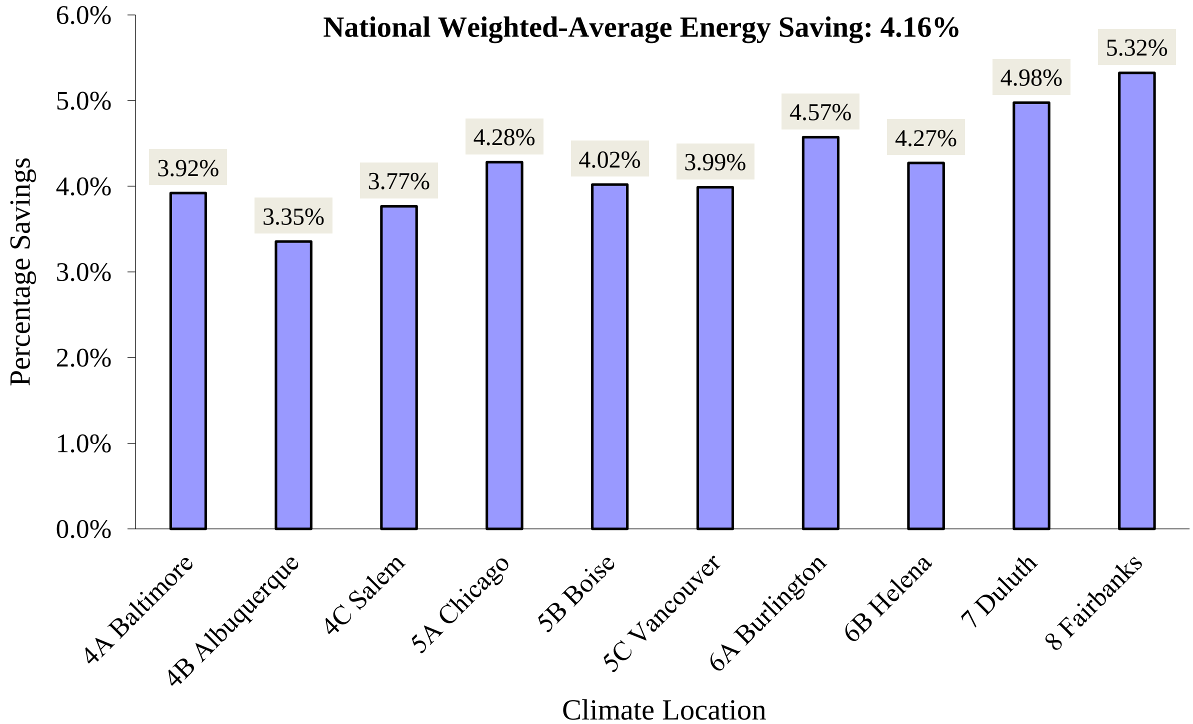

Figure 10: Percentage energy savings from ASHRAE 90.1 vestibule requirements for quick service restaurant building prototype

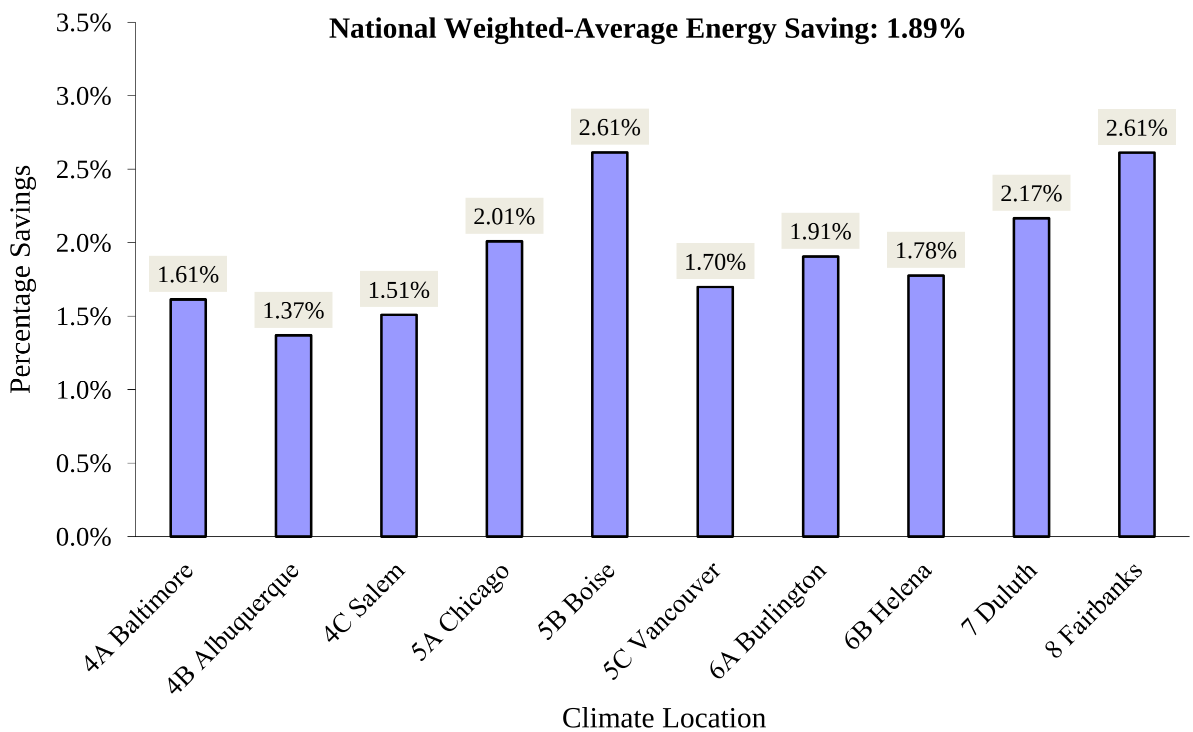

Figure 11: Percentage energy savings from ASHRAE 90.1 vestibule requirements for sit-down restaurant building prototype

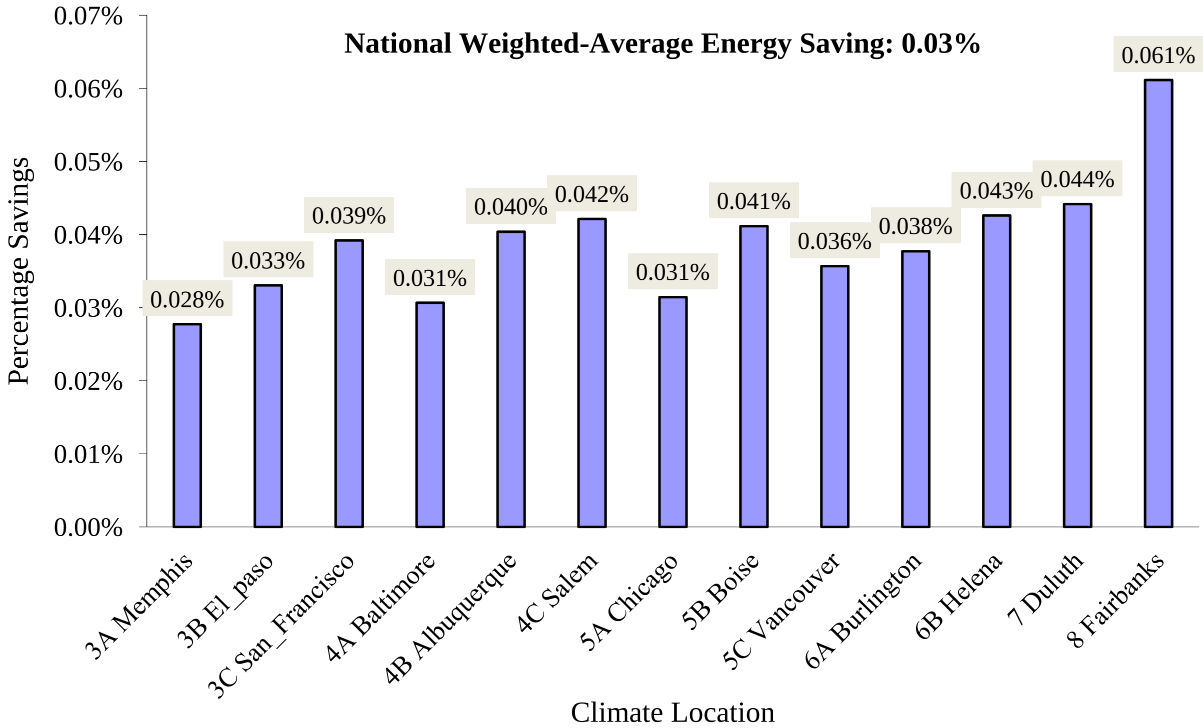

Figure 12: Percentage energy savings from ASHRAE 90.1 vestibule requirements for outpatient health care building prototype

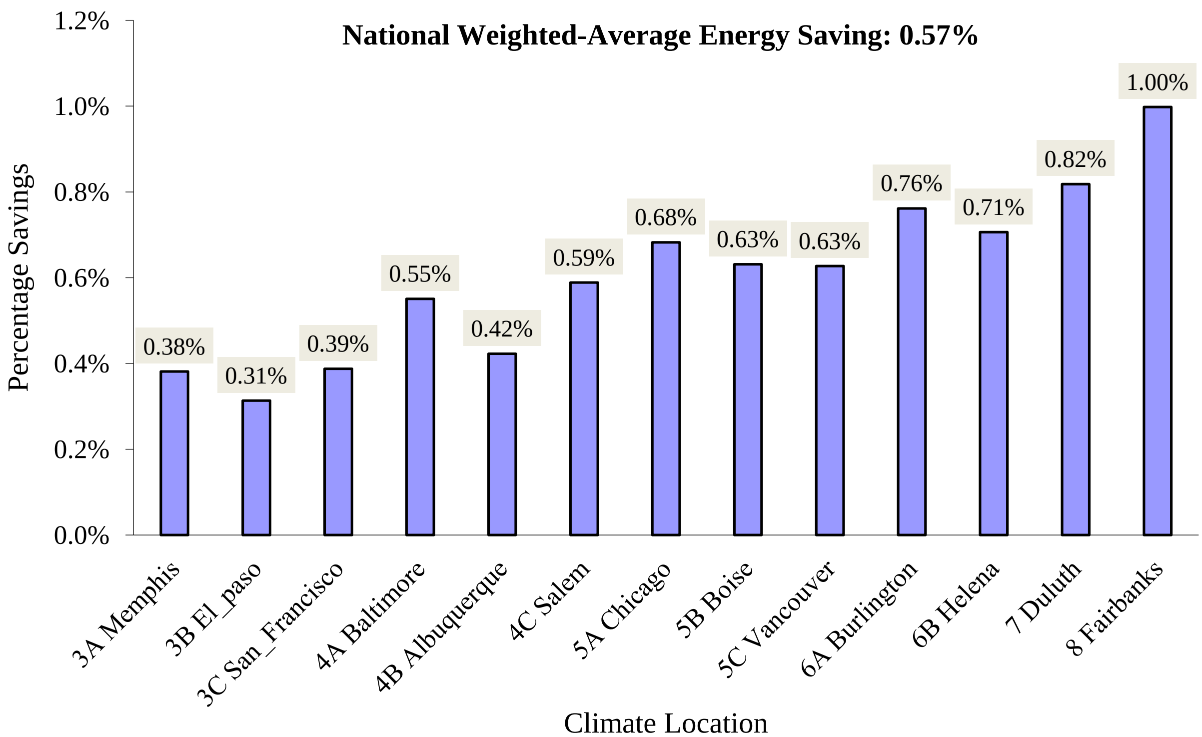

Figure 13: Percentage energy savings from ASHRAE 90.1 vestibule requirements for small hotel building prototype

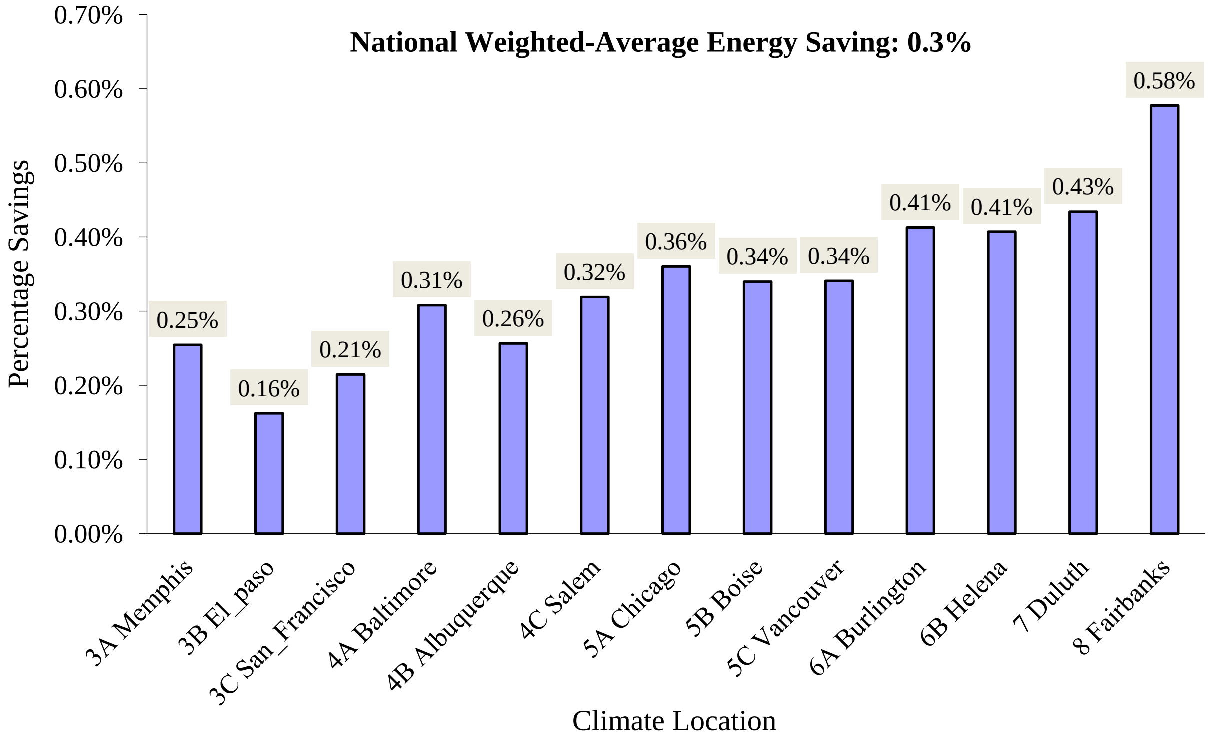

Figure 14: Percentage energy savings from ASHRAE 90.1 vestibule requirements for mid-rise apartment building prototype

7. Sensitivity Analysis

A sensitivity analysis was performed to quantify the influences of each variable such as outdoor temperature and door-opening frequency, on the final results. A quick service restaurant located in Baltimore MD was used in this analysis. First, the values of outdoor temperature and door-opening frequency were varied, as shown in Tables 9 and 10, respectively. Varying the outdoor temperature from 60°F to -40°F in Table 9 resulted in changes to the peak air infiltration rate of about 7% for this building. Thus, the outdoor temperature has little impact on the estimation of peak air infiltration rate through door openings using the ASHRAE method. On the other hand, the results in Table 10 show that changing the assumptions regarding door-opening frequency has a high contribution to the peak air infiltration rate through doors. It indicates that a good estimation of door-opening frequency (and door opening schedules) is more important in estimating peak air infiltration rate through door openings.

Table 9 Impact of outdoor temperature on the peak air infiltration rate through door openings

Outdoor Temperature [°F]*	Peak Air Infiltration Rate through Door openings [cfm]	Percentage Variation
80	1899	0.7 %
60 (Baseline)	1913	0 %
40	1940	1.4 %
20	1966	2.8 %
0	1993	4.2 %
-20	2020	5.6 %
-40	2046	7.0 %

* The range of outdoor temperature is selected to consider all the ranges shown in Figure 2.

Table 10 Impact of door-opening frequency on the peak air infiltration rate through door openings

Percentage Variation of Door-opening Frequency [%]	Door-opening Frequency [peak door openings per hour]	Peak Air Infiltration Rate through Door Openings [cfm]	Percentage Variation [%]
-30 %	63	1417	-26 %
-20 %	72	1585	-17 %
-10 %	81	1751	-8 %
Baseline	90	1913	0 %
10 %	99	2073	8 %
20 %	108	2231	17 %
30 %	117	2386	25 %

Next, the impact of variation on the air infiltration rates through door-openings has been examined, as shown in Table 11. It is seen that a reduction in the estimated infiltration rate per door opening of 20% results in a drop in the percentage savings estimate from the vestibule requirements from 3.93% to 3.20% (0.73% reduction). An increase in the estimated infiltration rate per door opening increases the percentage savings estimate by 0.7 percentage points. This indicates that within this range, a variation of infiltration rate per door-opening results in an essentially linear variation in the percentage energy savings.

Table 11 Impact of the air infiltration rates through door openings on percentage energy savings for quick service restaurant at Baltimore, MD

Variation on Infiltration Rate through Door Openings	Total Energy Consumption Building with Vestibule [MMBtu]	Total Energy Consumption Building without Vestibule [MMBtu]	Percentage Savings	Difference from Baseline
-20%	1,423	1,470	3.20%	0.73%
-10%	1,433	1,486	3.57%	0.36%
Baseline	1,443	1,502	3.93%	Baseline
10%	1,453	1,518	4.28%	0.35%
20%	1,463	1,534	4.63%	0.70%

8. Conclusions

A method to model air infiltration through the door openings was developed to estimate the energy saving impacts of two ASHRAE 90.1 vestibule requirements (i.e., addendum ‘c’ to ASHRAE Standard 90.1-2004 and addendum ‘q’ to ASHRAE Standard 90.1-2007). This report shows that the estimation of air infiltration rate using the proposed method can be readily incorporated into EnergyPlus whole building energy simulations to provide estimated percent site energy savings for different building types. PNNL’s prototypical commercial building models were used in the analysis to determine the percentage energy savings from these new vestibule requirements. All building prototypes were analyzed to see how each prototype would be affected by the vestibule requirements of ASHRAE 90.1. The door-opening frequency for each indentified building was estimated based on data from available literature or estimated using occupancy data.

Finally the energy savings for each building and each climate location was estimated. The results shows that strip mall, standalone retail, quick service restaurant, and sit-down restaurant building have larger percentage energy savings compared to other buildings. The simulation results show that the range of estimated energy savings from ASHRAE 90.1 vestibule requirements varied between 0.06% to 5.61% depending on building type when averaged over all 16 climate zones.

9. References

[1] U.S. Department of Energy (DOE). 2010. *Energy Efficiency Trends in Residential and Commercial Buildings*. Washington, D.C. Last accessed in November, 2010 and available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/building_trends_2010.pdf

[2] U.S. DOE. 2001. *Low-Energy Building Design Guidelines*. DOE/EE-0249, Washington, D.C. Last accessed in November, 2010 and available at: http://www1.eere.energy.gov/femp/pdfs/25807.pdf

[3] Gowri, K., D. Winiarski, and R. Jarnagin. 2009. *Infiltration Modeling Guidelines for Commercial Building Energy Analysis*. PNNL-18898, Pacific Northwest National Laboratory, Richland, WA.

[4] Yuill, G.K. 1996. *Impact of High Use Automatic Doors on Infiltration*. Project 763-TRP, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

[5] Kohri, K. 2001. *A Simulation Analysis of the Opening Area of Entrance Doors and Winter Airflow into the Entrance Hall of a High-rise Office Building*. Seventh International IBPSA Conference, Rio de Janeiro, Brazil.

[6] ASHRAE. 2009. *Handbook of Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

[7] U.S. DOE. 2009. *New Construction - Commercial Reference Buildings*. Last accessed in November, 2010 at: http://www1.eere.energy.gov/buildings/commercial_initiative/new_construction.html

[8] Liu, B., R.E. Jarnagin, D.W. Winiarski, W. Jiang, M.F. McBride and G.C. Crall. 2006. *Technical Support Document: Development of the Advanced Energy Design Guide for Small Retail Buildings*. PNNL-16031, Pacific Northwest National Laboratory. Richland, WA.

[9] Liu, B., R.E. Jarnagin, W. Jiang, and K. Gowri. 2007. *Technical Support Document: Development of the Advanced Energy Design Guide for Small Warehouse and Self-storage Buildings*. PNNL-17056, Pacific Northwest National Laboratory, Richland, WA.

[10] Jiang, W., K. Gowri, M.D. Lane, B.A. Thornton, M.I. Rosenberg, and B. Liu. 2009. *Technical Support Document: 50% Energy Savings Design Technology Packages for Highway Lodging Buildings*. PNNL-18773, Pacific Northwest National Laboratory, PNNL-18773, Richland, Washington.

[11] Thornton, B.A., W. Wang, Y. Huang, M.D. Lane, and B. Liu. 2009. *Technical Support Document: 50% Energy Savings Design Technology Packages for Small Office Building.* PNNL-19341, Pacific Northwest National Laboratory, PNNL-18773, Richland, WA.

[12] Energy Information Administration, 2003 Commercial Buildings Energy Consumption Survey, Last accessed in November, 2010 at: http://www.eia.doe.gov/emeu/cbecs/

[13] Claar, C.N., R.P. Mazzucchi, and J.A. Heidell, 1985. *The Project on Restaurant Energy Performance – End-use Monitoring and Analysis*, PNL-5462, Pacific Northwest National Laboratory, Richland, WA

[14] U.S. Department of Education. National Center for Education Statistics, Digest of Education Statistics 2007, Table 78: Staff employed in public elementary and secondary school systems, by type of assignment and state or jurisdiction: Fall 2005. Last accessed in November, 2010 at: http://nces.ed.gov/programs/digest/d07/tables/dt07_078.asp

[15] U.S. Department of Education, National Center for Education Statistics, Digest of Education Statistics 2007, Table 63: Teachers, enrollment, and pupil/teacher ratios in public elementary and secondary schools, by state or jurisdiction: Fall 2005. Last accessed in November, 2010 at: http://nces.ed.gov/programs/digest/d07/tables/dt07_063.asp

[16] American Hotel & Lodging Association. 2007. *The 2007 Lodging Industry Profile*. Washington, D.C. Last accessed in November, 2010 at: http://www.ahla.com/content.aspx?id=4214

APPENDIX A

APPENDIX A

ASHRAE 90.1-2004 requirement:

5.4.3.4 Vestibules. A door that separates *conditioned space* from the exterior shall be protected with an enclosed vestibule, with all *doors* opening into and out of the vestibule equipped with self-closing devices. Vestibules shall be designed so that in passing through the vestibule it is not necessary for the interior and exterior *doors* to open at the same time. Interior and exterior *doors* shall have a minimum distance between them of not less than 7 ft when in the closed position.

Exceptions to 5.4.3.4:

(a) *Doors* in buildings in climate zones 1 and 2.

(b) *Doors* in buildings less than four stories above grade.

(c) *Doors* not intended to be used as a *building entrance door,* such as mechanical or electrical equipment rooms.

(d) *Doors* opening directly from *dwelling unit.*

(e) *Doors* that open directly from a space less than 3000 ft^2 in area.

(f) *Doors* in building entrances with revolving *doors.*

(g) *Doors* used primarily to facilitate vehicular movement or material handling and adjacent personnel doors.

ASHRAE 90.1-2007 requirement (addenda 'c' to ASHRAE 90.1-2004):

5.4.3.4 Vestibules. A door that separates *conditioned space* from the exterior shall be protected with an enclosed vestibule, with all *doors* opening into and out of the vestibule equipped with self-closing devices. Vestibules shall be designed so that in passing through the vestibule it is not necessary for the interior and exterior *doors* to open at the same time. Interior and exterior *doors* shall have a minimum distance between them of not less than 7 ft when in the closed position. The exterior envelope of conditioned vestibules shall comply with the requirements for a conditioned space. The interior and exterior envelope of unconditioned vestibules shall comply with the requirements for a semiheated space.

Exceptions:

(a) *Building entrances* with revolving *doors*.

(b) *Doors* not intended to be used as a *building entrance.*

(c) *Doors* opening directly from *dwelling unit.*

(d) *Building entrances* in buildings located in climate zone 1 or 2.

(e) *Building entrances* in buildings located in climate zone 3 or 4 that are less than four stories above grade and less than 10,000 ft^2 in area.

(f) *Building entrances* in buildings located in climate zone 5, 6, 7, or 8 that are less than 1,000 ft^2 in area.

(g) *Doors* that open directly from a *space* that is less than 3000 ft^2 in area and is separate from the *building entrance*.

<u>Addendum 'q' to ASHRAE 90.1-2007:</u>

5.4.3.4 Vestibules. Building entrances that separate *conditioned space* from the exterior shall be protected with an enclosed vestibule, with all *doors* opening into and out of the vestibule equipped with self-closing devices. Vestibules shall be designed so that in passing through the vestibule it is not necessary for the interior and exterior *doors* to open at the same time. Interior and exterior *doors* shall have a minimum distance between them of not less than 7 ft when in the closed position. The exterior envelope of conditioned vestibules shall comply with the requirements for a conditioned space. The interior and exterior envelope of unconditioned vestibules shall comply with the requirements for a semiheated space.

Exceptions:

(h) *Building entrances* with revolving *doors*.

(i) *Doors* not intended to be used as a *building entrance*.

(j) *Doors* opening directly from *dwelling unit.*

(k) *Building entrances* in buildings located in climate zone 1 or 2.

(l) *Building entrances* in buildings located in climate zone 3 that are less than four stories above grade and less than 10,000 ft^2 in area.

(m) *Building entrances* in buildings located in climate zone 4, 5, 6, 7, or 8 that are less than 1,000 ft^2 in area.

(n) *Doors* that open directly from a *space* that is less than 3000 ft^2 in area and is separate from the *building entrance*.

(Note: Addenda 'q', deletes Zone 4 from exception (e), and adds Zone 4 to exception (f)).

Pacific Northwest
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)
www.pnl.gov