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Air Leakage Through Automatic Doors

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ABSTRACT

A method has been developed to estimate the air leakage through high-use automatic doors. This air leakage is specified as a function of the rate of use of the door, the door geometry, and the pressure difference across the door. Two studies were carried out to obtain these results. One was a laboratory study of the discharge coefficients of doors of various geometries. The other was a field study of the times when automatic doors are open as a function of use. The results of the field study were analyzed and combined with the discharge coefficients that were measured in the laboratory study. The result was an air flow coefficient that is a function of the number of people using a door each hour. The designer can use this coefficient with the pressure difference across the door to estimate the rate of air leakage through the door.

INTRODUCTION

A simple method has been developed by which design engineers can estimate the infiltration rates into buildings due to the opening of automatic doors. The results of this work are summarized in a graph relating an airflow coefficient to the rate of use of a door, in people per hour. The designer need only determine this coefficient and then multiply it by the door area and the square root of the pressure difference across the door to obtain the infiltration rate. This work was proposed by ASHRAE Technical Committee 4.3, Ventilation Requirements and Infiltration, and was supported by ASHRAE Research Project 763.

Figure 1 shows the relationship between the airflow coefficient and the rate of use for doors with and without vestibules. The curves of the figure are averages for sets of doors that behave similarly.

Two studies were carried out to obtain the results included here. One was a laboratory study of the discharge coefficients of doors of various geometries. The other was a field study of the times when automatic doors are open as a function of use. The final results, shown in Figure 1, were obtained by an analysis that combined the results of these two studies.

The laboratory study was carried out in a one-third-scale test facility. An airtight room was constructed with a door in one end and a flowmeter and fan in the other end. The fan was used to depressurize the room, and the flowmeter measured the fan flow and, thus, the flow through the door. The pressure difference across the door was measured, and the discharge coefficient of the door could be calculated from the flow and the pressure difference.

This process was repeated for a variety of different doors, including swinging and sliding single and double doors, in walls and in vestibules. The vestibules were configured with the outer doors opposite the inner doors or in the sides of the vestibule. The doors were tested in several positions ranging from fully open to almost closed. They were also tested with a suitably sized doll in the open doorway to determine the effect of door users on flow rate. In each configuration, a series of tests was performed at a range of pressures from about 5 Pa to about 50 Pa. A total of 1456 tests were made of 15 door configurations in 151 door positions.

The field study was carried out by observers at five different locations in North America. They began by making a series of basic measurements on the automatic door. They measured the "base open time," the minimum time it would take the door to open and close if no user went through it. They measured the time to reach the fully open position, the time in the fully open position, the time to close to the "slow close gap" position, the

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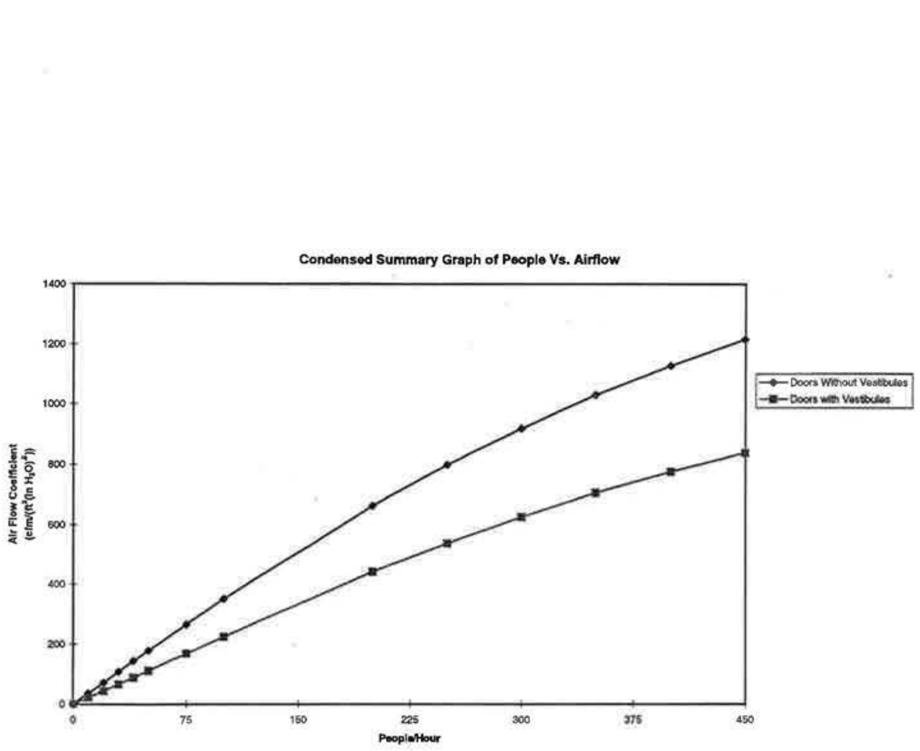

Figure 1 *Condensed summary graph of people vs. airflow.*

time to close slowly the remainder of the way, and the width of the "slow close gap." When these preliminary measurements were complete, the observers watched each door studied for a period of several hours. During that time, they recorded each use of the door. For each use, the total time open was measured, and the number of people passing through the door was recorded by sex and age. A total of 381 hours of door observations on 109 doors was recorded. This included 15,800 door openings and 41,529 people.

The results of the field study were analyzed, and two correlations were obtained that predicted the total time that a door would be open. The first was a prediction of the fraction of time that a door would be open as a function of the number of people using the door per hour. The second was a prediction of the number of door openings per hour, again as a function of the number of people using the door per hour.

In developing these correlations, it was found that an important factor was the "base open time" of the door. A good correlation could be found only when the data were corrected to the average "base open time." It was also found that several other variables had only insignificant effects on the fraction of time the door was open. These included geographical location, building use, fraction of elderly users, and outdoor temperature.

One variable that was statistically significant was the fraction of children in the group of people using the door. However, this variable was not accounted for in the final correlation. This was done because the effect, although statistically significant, was small compared to the uncertainties that a design engineer would face when applying this design procedure. Therefore, it was decided to ignore the effect of children to keep the procedure simple. Also, no test data were collected in schools because none were found with automatic doors. This means that the results would be meaningful only for the types of buildings tested, where most children were young children with their parents. It is unlikely that a designer would have meaningful data about the fraction of children that would be expected to use a door in these types of buildings, other than the average data collected in the present study. Of course, the correlations developed in the present study already account for this average fraction of children.

These correlations were then combined with the discharge coefficients that were measured in the laboratory for all the different types of doors and the range of door positions. This was done by developing expressions for the door discharge coefficients as functions of the fraction of time that the door was open. These expressions were then integrated over each of the time periods involved in the use of a door: the opening period, the wide open period, the closing period, and the slow close period. The average discharge coefficients for the door opening event were then found. Since the number of events per hour was known as a function of the usage rate, the result was a set of airflow coefficients as functions of the hourly rate of door use (people per hour), for each door configuration. These airflow coefficients are shown in Figure 1. To use them, the designer must first calculate the pressure differential across the door, based on the wind and stack effects and on the effect of the operation of mechanical ventilation systems, using the methodology of *ASHRAE Fundamentals* (ASHRAE 1993). Then the airflow coefficient is multiplied by the area of the door and by the square root of the pressure differential to get the hourly average air leakage rate through the door.

LABORATORY STUDY

Objective

The objective of this study was to determine the discharge coefficients (C_D) of a range of door configurations, with the doors partially and fully opened. This study was performed for simulations of sliding doors, single and double swinging doors, and a fully open door with a person in the doorway. For the cases of swinging doors, the coefficients were measured with the angle of the door swings at 30°, 60°, and 90°. For sliding doors, they were measured with the doors at 1/8 open, 1/2 open, 3/8 open, and 3/4 open. Ten different vestibule configurations were also studied, with single and double swinging and sliding doors on the front and on the side of the vestibule. In the final report to ASHRAE, Yuill (1999) presents the details of the configurations.

Experiment

Description of Apparatus. The apparatus used to measure the discharge coefficients was designed to simulate the entrance to a building at one-third scale. The main chamber of the apparatus consists of an airtight box 2.44 m by 2.44 m by 1.3 m (96 in. × 96 in. × 51in.). The box had an opening 0.61 m by 0.71 m (24 in. × 28.25 in.) on one side, with a pair of hinged panels, to represent a double doorway. When a single door was simulated, one of the doors was closed and taped shut. Directly across from the door opening on the other side of the chamber was an opening containing an exhaust fan and a bell-mouthed nozzle flowmeter.

In addition to the main chamber, there was also a "vestibule" attachment. This consisted of a smaller box, 1.22 m by 0.91 m by 0.94 m (48 in. × 36 in. × 37 in.), open on one side. This open side was placed on the wall of the main chamber, covering the door. The other three sides of the vestibule all had openings, each with a pair of hinged panels, to represent a double doorway. The door openings not being used for a particular simulation were closed and taped shut. Thus, this attachment could simulate a vestibule with various door entry configurations.

Measured Data. Twenty entry configurations were studied, each with the doors in several different positions, for a total of 143 cases. For each entry configuration and door position simulated, the blower door was used to measure the air flow through the doors, the changes in pressure through each door (ΔP_1 or ΔP_2), and the pressure change over the entire vestibule (ΔP_3) when applicable. For each configuration of each case simulated, several trials were run at different air flows and the results correlated to find the exponent and the coefficient. It was found that the measured exponents associated with the pressure differentials were very nearly equal to 0.5 in every case. This indicates that potential flow dominated the results. Therefore, it is unlikely that the results were affected by the one-third scale used for this experiment.

Analysis of Data. For each run, all pertinent discharge coefficients were found using the measured data and the equation (ASHRAE 1993, p. 23.7, Eq.14)

$$C_D = Q/(A \cdot (2g_c \Delta P/\rho)^{.5})$$

where

C_D = discharge coefficient,

Q = volumetric flow rate,

A = area of the doorway,

g_c = dimensional constant = 32.174 $lb_m\,ft/lb_f\,s^2$ (= 1 in SI units),

ΔP = pressure differential from one side to the other,

ρ = density of the air.

The discharge coefficients (C_D) are based on the area of the doorway. Therefore, they account not only for the deviation of the flow pattern from the ideal but also for the restriction of the flow area due to the partial closing of the door.

For the vestibule cases, two other coefficients were calculated from the measured data. For each vestibule configuration, an ideal coefficient, C_{DI}, was calculated based on the calculated values of C_D for each door on either side of the vestibule if that door were alone in a wall. C_{DI}, therefore, represents the resulting discharge coefficient of two doors in series if the velocity of the air flowing through the first door is completely dissipated before it reaches the second door. The coefficient is given by

$$C_{DI} = C_{D1}/(C_{D1}^2 / C_{D2}^2 + 1) \quad (1)$$

where

C_{DI} = ideal flow coefficient,

C_{D1} = flow coefficient for the inner door standing alone,

C_{D2} = flow coefficient for the outer door standing alone.

The second coefficient calculated for the vestibules was the vestibule coefficient C_v, which represents the ratio of the measured C_D coefficient for the vestibule to the ideal C_{DI} coefficient:

$$C_v = C_D/C_{DI} \quad (2)$$

Results

In general, the swinging doors had higher discharge coefficients than the sliding doors and the vestibules had lower discharge coefficients than doors with no vestibule. Yuill (1999) presented the detailed results of these measurements.

FIELD OBSERVATIONS

Objective

The objective of these observations was to determine the relationship between the number of people passing through a door or vestibule in an hour and the open time per hour of the door or vestibule. Measurements were taken and observations were made for varying types of doorways and vestibules at several North American locations under different weather conditions.

Observations

Observations were made of door usage in Pennsylvania, Texas, Virginia, the District of Columbia, and Manitoba. A total of 109 doors were studied over a total of 381 hours. This survey included a general description of each doorway or vestibule and observations of the times for which doors were open when people entered and left the buildings.

General Information Recorded.

Building Description—The number of floors, size, and building type.

Weather Data—The outdoor temperature, wind speed, and wind direction.

Door Description—The number of doors, type of doors, traffic patterns, type of mechanism used to open the door, and the door position (separating the interior from the exterior, separating the interior from the vestibule, or separating the vestibule from the exterior).

Sketch—A sketch of each entry observed was included that indicated the swings of the doors, the size of the vestibule if applicable, the placement of the doors in relation to one another, and the measured fully open width of each doorway.

Measured Data Recorded.

Base Open Time—The base open time refers to the entire time from when a door begins to open from the fully closed position to the time it returns to the fully closed position when no people pass through the door. This time was found for each door by averaging the measured times of ten trials in which the opening mechanism was activated and the door was allowed to fully open and fully close without anyone passing through.

Opening and Closing Times—The time taken for the door to move from the completely closed position to the completely open position and the time taken for the door to move from the completely open position to the completely closed position were measured for each door. For these measurements, fifteen trials were timed and averaged for each door observed.

Slow Close Time—Many doors have two closing speeds. They close quickly until they are almost closed and then close slowly for the last few inches. This slow closing time was measured and then averaged over ten trials. Also, the width of the open gap just before the slow close was measured.

Lag Times Between Vestibule Doors—For vestibule cases, the lag times between the opening of the inner door and the outer door and the closing of the inner door and the outer door were also measured. For these measurements, 15 trials were timed for each door observed.

Open Times Plus Number and Types of People—Observations were made for each doorway over a long period of time, during which the number of people and the open time were measured for each use. The types of people were also noted (child, male, female, elderly male, and elderly female).

Results

Averaged Data. The results used in the analysis were as follows:

Base open time, sliding door	= 8.3 s
Base open time, swinging door	= 11.71 s
Average ratio of slow close gap to door width, sliding door	= .069
Average ratio of slow close gap to door width, swinging door	= .086
Slow close time, sliding door	= 1.47 s
Slow close time, swinging door	= 3.12 s
Total opening time, all doors	= 3.27 s
Total closing time, all doors	= 4.15 s
Time lag between openings of doors in vestibule, all doors	= 2.83 s
Time lag between closings of doors in vestibule, all doors	= 2.67 s

Table 1 lists the data recorded for each of the doors studied and Table 2 contains the results from a more detailed study that was performed to establish the opening time, fully open time, and closing time of automatic doors.

Determination of Basic Relationships. Relationships between some aspects of the recorded data were also needed for the analysis. It was necessary to find the number of people per use (P_u) and the fractional open time (T_h), both as functions of the number of people per hour (P_h). For people per use, linear correlations were found for both sliding and swinging doors. For open time per hour, an exponential correlation was used. The resulting equations were:

$$P_u \text{ (swinging doors)} = 0.0098 \cdot P_h + 1.7541 \quad (3)$$

$$P_u \text{ (sliding doors)} = 0.0052 \cdot P_h + 1.4527 \quad (4)$$

$$T_h = 1 - \exp(-0.002233 \cdot P_h) \text{ (single door)} \quad (5)$$

$$T_h = (1 - \exp(-0.002233 \cdot P_h)) - 0.00041 \cdot U_h \text{ (vestibule)} \quad (6)$$

Figure 2 shows the people per use as a function of the people per hour, for both swinging doors and sliding doors. Figure 3 shows the fraction of time that the door is open as a function of the people per hour.

The effects of location, type of building, outdoor temperature, age of people passing through the doorways, and shopping carts were also studied. The effects of these parameters, however, were not significant enough to warrant the complications that would have arisen from including them in the analysis; therefore, they were disregarded.

ANALYSIS

Objective

The objective of this analysis was to combine the experimental data on the flow coefficients of doors and the observed data on door usage to determine the relationship between the number of people per hour using an automatic door and the hourly air flow through the door. This relationship was examined for swinging and sliding doors with and without vestibules.

TABLE 1
Data and Analysis for Individual Cases

GLOSSARY OF COLUMN HEADINGS	
Base Open Time	Time required for door to open and close automatically without being used
Percent Children	Percent of users estimated to be under 12 years old
Percent Adult	Percent of users estimated to be between 12 and 65 years old
Percent Elderly	Percent of users estimated to be over 65 years old
Percent Carts	Percent of uses when a cart passed through the door with the user(s)
Data Open Fraction	Fraction of time the door was open during observation period
Model Open Fraction	Fraction of time door is predicted to be open by a model of the door data

Observer	Type	Location (State)	Type of Door	Traffic Pattern	Door Configuration: Interior or exterior door with or without vestibule	Outside Temperature (°F)	Base Open Time (sec)	Open Time (sec) during observation period	Number of Uses	Hours of Data Collected	Uses per Hour	Percent Children	Percent Adult	Percent Elderly	Percent Cart	People per Use	People per Hour	Data Open Fraction—Uncorrected	Model Open Fraction—Uncorrected	Data Open Fraction—Base Open Time Corrected	Model Open Fraction—Base Open Time Corrected
AA1	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	57	11.58	1287	95	3.33	29	22	75	3	0	1.7	48	0.11	0.10	0.09	0.10
AA2	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	64	6.23	4079	267	2.67	100	16	82	2	0	3.3	332	0.42	0.51	0.51	0.52
AA3	RETAIL	PA	SWING	1-WAY	EXT/VEST	51	6.31	949	101	3.00	34	8	91	1	0	1.4	49	0.09	0.10	0.12	0.10
AA4	RETAIL	PA	SWING	1-WAY	EXT/VEST	70	7.89	4410	315	4.00	79	13	82	5	0	3.4	270	0.31	0.44	0.34	0.45
AA5	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	58	7.97	1423	141	4.00	35	11	83	6	0	1.6	58	0.10	0.12	0.11	0.12
AA6	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	65	7.85	1711	123	2.00	62	21	68	11	0	2.5	152	0.24	0.28	0.26	0.29
AA7	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	60	9.05	2144	137	3.50	39	17	64	19	0	2.4	96	0.17	0.19	0.17	0.19
AA8	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	77	8.36	1516	117	3.00	39	21	65	13	0	1.9	73	0.14	0.15	0.15	0.15
AA9	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	75	8.02	1332	113	4.00	28	8	79	13	0	1.9	53	0.09	0.11	0.10	0.11
AA10	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	86	8.03	1580	134	4.00	34	9	80	11	0	2.0	66	0.11	0.13	0.12	0.14
AA11	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	80	8.09	1329	110	3.25	34	12	74	14	0	2.1	71	0.11	0.14	0.13	0.15
AK1	RETAIL	PA	SWING	1-WAY	EXT/INT	55	9.57	636	34	2.00	17	16	41	43	0	1.5	26	0.09	0.05	0.09	0.06
AK2	RETAIL	PA	SWING	2-WAY	EXT/VEST	46	5.45	341	30	2.00	15	12	56	33	0	1.7	26	0.05	0.05	0.06	0.06
AK3	RETAIL	PA	SWING	2-WAY	EXT/VEST	46	9.38	571	30	2.00	15	12	67	21	0	2.2	34	0.08	0.07	0.08	0.07
CH1a	RETAIL	TX	SWING	1-WAY	INT/VEST	67	14.56	1017	59	8.00	7	20	73	7	20	2.7	20	0.04	0.04	0.02	0.04
CH1b	RETAIL	TX	SWING	1-WAY	EXT/VEST	67	16.25	1103	59	8.00	7	24	70	6	19	3.3	24	0.04	0.05	0.02	0.05

TABLE 1 (Continued)
Data and Analysis for Individual Cases

Observer	Type	Location (State)	Type of Door	Traffic Pattern	Door Configuration: Interior or exterior door with or without vestibule	Outside Temperature (°F)	Base Open Time (sec)	Open Time (sec) during observation period	Number of Uses	Hours of Data Collected	Uses per Hour	Percent Children	Percent Adult	Percent Elderly	Percent Cart	People per Use	People per Hour	Data Open Fraction—Uncorrected	Model Open Fraction—Uncorrected	Data Open Fraction—Base Open Time Corrected	Model Open Fraction—Base Open Time Corrected
CH1c	RETAIL	TX	SWING	1-WAY	INT/VEST	67	15.15	1021	59	8.00	7	19	74	6	15	2.5	19	0.04	0.04	0.02	0.04
CH1d	RETAIL	TX	SWING	1-WAY	EXT/VEST	67	15.63	1077	59	8.00	7	17	78	5	0	3.2	24	0.04	0.05	0.02	0.05
CH2	RETAIL	TX	SWING	1-WAY	EXT/INT	82	14.15	2078	115	5.20	22	20	73	7	15	3.4	75	0.11	0.15	0.08	0.15
CH3	RETAIL	TX	SLIDE	2-WAY	EXT/INT	70	9.66	1937	113	4.20	27	19	73	8	1	3.3	88	0.13	0.17	0.13	0.18
CH4	RETAIL	TX	SLIDE	2-WAY	EXT/INT	72	8.50	1283	100	4.25	24	16	76	8	2	2.3	55	0.08	0.11	0.09	0.12
CH5	RETAIL	TX	SLIDE	2-WAY	EXT/INT	72	8.22	1508	112	4.20	27	14	81	5	1	2.8	75	0.10	0.15	0.11	0.16
CH6	RETAIL	TX	SLIDE	1-WAY	EXT/INT	74	10.42	2115	118	5.00	24	17	76	7	5	2.9	69	0.12	0.14	0.11	0.14
CH7	RETAIL	TX	SWING	2-WAY	EXT/INT	70	9.41	1770	119	5.25	23	17	76	7	18	4.0	91	0.09	0.18	0.09	0.18
CH8	RETAIL	TX	SWING	2-WAY	INT/VEST	66	11.54	984	59	4.50	13	21	61	19	3	2.8	37	0.06	0.08	0.05	0.08
CH8b	RETAIL	TX	SWING	2-WAY	INT/VEST	66	11.48	933	59	4.50	13	20	68	12	20	2.5	33	0.06	0.07	0.05	0.07
CH9	RETAIL	TX	SWING	2-WAY	INT/VEST	70	12.25	958	59	4.50	13	20	74	6	24	2.7	36	0.06	0.07	0.05	0.08
CH9b	RETAIL	TX	SWING	2-WAY	INT/VEST	70	8.76	871	59	4.50	13	20	72	8	0	2.0	26	0.05	0.06	0.06	0.06
DB1	HOSP.	PA	SLIDE	2-WAY	EXT/INT	65	5.66	874	81	4.40	18	1	60	39	3	1.3	25	0.06	0.05	0.07	0.05
DB2	HOSP.	PA	SLIDE	2-WAY	EXT/INT	70	9.37	1155	89	2.25	40	8	66	27	4	1.9	76	0.14	0.15	0.14	0.16
DB3	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	72	8.31	2645	200	3.17	63	8	70	22	4	2.3	144	0.23	0.27	0.25	0.27
DB4	HOSP.	PA	SLIDE	2-WAY	EXT/INT	68	5.66	427	36	1.88	19	0	65	35	0	1.2	23	0.06	0.05	0.08	0.05
DB5	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	68	8.31	1666	123	0.75	164	12	69	18	6	2.7	441	0.62	0.61	0.67	0.63
DB6	MEDICAL	PA	SLIDE	2-WAY	EXT/VEST	76	7.98	2281	203	4.00	51	4	68	28	1	1.7	85	0.16	0.17	0.18	0.17
DB7	MEDICAL	PA	SLIDE	2-WAY	EXT/VEST	76	11.44	2587	173	3.00	58	5	72	23	2	1.8	101	0.24	0.20	0.21	0.20
DB8	HOTEL	PA	SLIDE	2-WAY	INT/VEST	66	14.55	822	48	2.00	24	0	100	0	4	1.5	35	0.11	0.07	0.08	0.08
DB9	HOSP.	PA	SLIDE	2-WAY	EXT/INT	66	5.66	1439	122	4.00	31	1	85	14	2	1.5	45	0.10	0.09	0.13	0.10
DB10	RETAIL	PA	SWING	1-WAY	INT/VEST	62	16.95	2578	60	1.90	32	13	62	25	16	4.6	146	0.38	0.27	0.31	0.28
DB11	HOSP.	PA	SLIDE	2-WAY	EXT/VEST	73	6.50	417	38	2.22	17	5	95	0	0	1.2	20	0.05	0.04	0.07	0.04
DB12	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	68	8.62	1876	141	3.58	39	12	76	13	1	1.7	69	0.15	0.14	0.15	0.14
DB13	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	74	6.41	2389	169	3.00	56	14	69	17	2	2.1	120	0.22	0.23	0.27	0.24
DB14	MEDICAL	PA	SLIDE	2-WAY	INT/VEST	77	7.93	2126	186	4.00	47	3	70	26	2	1.6	74	0.15	0.15	0.17	0.15

TABLE 1 (Continued)
Data and Analysis for Individual Cases

Observer	Type	Location (State)	Type of Door	Traffic Pattern	Door Configuration: Interior or exterior door with or without vestibule	Outside Temperature (°F)	Base Open Time (sec)	Open Time (sec) during observation period	Number of Uses	Hours of Data Collected	Uses per Hour	Percent Children	Percent Adult	Percent Elderly	Percent Cart	People per Use	People per Hour	Data Open Fraction—Uncorrected	Model Open Fraction—Uncorrected	Data Open Fraction—Base Open Time Corrected	Model Open Fraction—Base Open Time Corrected
DB15	RETAIL	PA	SLIDE	2-WAY	INT/VEST	77	6.43	2388	220	4.00	55	11	82	8	3	1.7	96	0.17	0.19	0.21	0.19
DB16	MEDICAL	PA	SLIDE	2-WAY	EXT/VEST	85	6.43	3476	230	4.00	58	7	70	23	1	2.1	124	0.24	0.23	0.29	0.24
DB17	HOTEL	PA	SLIDE	2-WAY	EXT/VEST	87	10.84	3223	184	4.00	46	7	85	8	6	2.2	101	0.22	0.20	0.21	0.20
DB18	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	107	8.90	6628	406	6.50	62	11	72	17	15	2.6	164	0.28	0.30	0.29	0.31
DB20	HOSP.	PA	SLIDE	2-WAY	INT/VEST	79	4.74	443	55	3.25	17	0	82	18	10	1.1	19	0.04	0.04	0.06	0.04
DB21	MEDICAL	PA	SLIDE	2-WAY	EXT/VEST	76	7.83	2664	238	4.00	60	6	69	25	0	1.7	101	0.19	0.19	0.21	0.20
DB22	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	76	6.42	3193	215	3.50	61	12	82	6	5	2.1	131	0.25	0.25	0.30	0.25
DB23	RETAIL	PA	SWING	1-WAY	INT/VEST	70	18.81	1809	33	1.00	33	16	68	15	15	5.2	170	0.50	0.31	0.42	0.32
DB24	HOSP.	PA	SLIDE	2-WAY	EXT/VEST	80	27.47	4778	161	3.00	54	0	89	11	12	1.8	94	0.44	0.18	0.17	0.19
DB25	RETAIL	PA	SWING	1-WAY	INT/VEST	80	20.16	4400	69	2.00	35	18	62	20	12	7.7	266	0.61	0.44	0.51	0.45
DB26	RETAIL	PA	SWING	1-WAY	INT/VEST	87	18.81	5292	151	3.50	43	0	74	26	18	2.8	119	0.42	0.23	0.31	0.23
DB27	RETAIL	PA	SLIDE	2-WAY	INT/VEST	87	6.83	2057	174	5.00	35	11	80	9	1	1.8	62	0.11	0.13	0.14	0.13
DB28	MEDICAL	PA	SLIDE	2-WAY	INT/VEST	87	8.14	792	74	1.50	49	6	83	11	2	1.6	81	0.15	0.16	0.16	0.17
DB29	MEDICAL	PA	SLIDE	2-WAY	EXT/VEST	87	6.35	1600	120	2.00	60	4	73	22	1	2.1	125	0.22	0.24	0.27	0.24
DB30	HOSP.	PA	SLIDE	2-WAY	INT/VEST	70	4.77	424	51	4.00	13	0	92	8	3	1.3	16	0.03	0.03	0.05	0.04
DB31	HOSP.	PA	SLIDE	2-WAY	INT/VEST	70	5.03	1014	113	4.00	28	4	80	16	9	1.4	39	0.07	0.08	0.10	0.08
DB32	MEDICAL	PA	SLIDE	2-WAY	EXT/VEST	70	7.30	1842	164	3.50	47	0	79	21	1	1.4	67	0.15	0.13	0.17	0.14
DB33	MEDICAL	PA	SLIDE	2-WAY	INT/INT	96	8.32	886	77	3.00	26	0	92	8	4	1.5	38	0.08	0.08	0.09	0.08
DB34	MEDICAL	PA	SLIDE	2-WAY	INT/VEST	96	8.57	561	43	0.50	86	5	69	26	5	2.0	174	0.31	0.31	0.33	0.32
DB35	MEDICAL	PA	SLIDE	2-WAY	EXT/VEST	96	8.03	991	91	2.00	46	1	90	9	1	1.5	67	0.14	0.13	0.15	0.14
DB36	HOSP.	PA	SLIDE	2-WAY	EXT/VEST	93	6.75	1188	97	3.25	30	0	58	42	4	1.8	53	0.10	0.11	0.12	0.11
DB37	HOSP.	PA	SLIDE	2-WAY	EXT/VEST	93	6.75	1139	96	2.75	35	1	58	41	6	1.9	67	0.12	0.13	0.14	0.14
DB38	RETAIL	PA	SWING	1-WAY	EXT/VEST	91	8.26	1393	111	1.75	63	8	72	20	19	1.7	109	0.22	0.21	0.24	0.22
DB39	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	91	9.52	2353	169	3.00	56	0	85	15	4	1.6	91	0.22	0.18	0.22	0.18
DB40	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	91	9.52	1422	102	2.00	51	0	95	5	1	1.7	87	0.20	0.17	0.20	0.18
DB41	RETAIL	PA	SWING	1-WAY	EXT/VEST	90	8.26	2122	151	2.00	76	16	66	18	19	2.4	183	0.29	0.33	0.32	0.34

TABLE 1 (Continued)
Data and Analysis for Individual Cases

Observer	Type	Location (State)	Type of Door	Traffic Pattern	Door Configuration: Interior or exterior door with or without vestibule	Outside Temperature (°F)	Base Open Time (sec)	Open Time (sec) during observation period	Number of Uses	Hours of Data Collected	Uses per Hour	Percent Children	Percent Adult	Percent Elderly	Percent Cart	People per Use	People per Hour	Data Open Fraction—Uncorrected	Model Open Fraction—Uncorrected	Data Open Fraction—Base Open Time Corrected	Model Open Fraction—Base Open Time Corrected
DB42	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	90	9.08	3753	277	3.00	92	6	86	8	11	1.8	171	0.35	0.31	0.35	0.32
DB44	HOTEL	PA	SLIDE	2-WAY	INT/VEST	90	14.49	1943	98	2.50	39	2	95	3	2	1.9	74	0.22	0.15	0.16	0.15
DB45	HOTEL	PA	SLIDE	2-WAY	EXT/VEST	90	11.55	1654	98	2.00	49	4	81	15	10	2.0	97	0.23	0.19	0.20	0.19
DB46	HOSP.	PA	SLIDE	2-WAY	INT/VEST	90	6.55	1535	124	4.00	31	3	49	48	8	1.8	57	0.11	0.11	0.13	0.12
DB47	MEDICAL	PA	SLIDE	2-WAY	INT/VEST	82	7.86	2280	208	3.50	59	3	83	14	1	1.5	91	0.18	0.18	0.21	0.18
DB48	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	82	6.98	2525	178	2.50	71	13	80	7	4	2.0	144	0.28	0.27	0.33	0.27
DB49	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	71	9.22	3868	250	4.00	63	10	76	14	11	2.4	153	0.27	0.28	0.27	0.29
DB50	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	86	9.08	2377	190	4.00	48	9	80	11	10	1.7	83	0.17	0.16	0.17	0.17
DB51	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	79	7.64	3741	278	5.00	56	5	84	11	5	2.0	114	0.21	0.22	0.23	0.22
DB52	HOSP.	PA	SLIDE	2-WAY	INT/VEST	67	8.67	1409	84	2.00	42	7	68	26	1	2.1	90	0.20	0.18	0.20	0.18
DB53	RETAIL	PA	SWING	1-WAY	INT/VEST	72	11.91	4790	181	3.50	52	20	61	18	13	4.5	231	0.38	0.39	0.34	0.40
DB54	RETAIL	PA	SLIDE	2-WAY	EXT/VEST	70	9.93	3350	161	2.50	64	32	38	30	26	2.8	183	0.37	0.33	0.36	0.34
DB55	RETAIL	VA	SWING	1-WAY	EXT/VEST	93	9.34	3762	182	2.00	91	16	78	6	15	4.3	396	0.52	0.57	0.52	0.59
DB56	HOSP.	VA	SLIDE	2-WAY	INT/VEST	91	7.62	2496	232	4.00	58	5	84	11	4	1.7	98	0.17	0.19	0.20	0.20
DB57	HOSP.	VA	SWING	2-WAY	INT/VEST	91	25.36	1280	44	1.25	35	0	100	0	8	1.5	51	0.28	0.10	0.13	0.11
DB58	HOSP.	VA	SLIDE	2-WAY	INT/VEST	91	7.62	2091	175	2.25	78	9	82	10	6	2.1	164	0.26	0.30	0.30	0.31
DB59	AIRPORT	DC	SWING	1-WAY	INT/VEST	95	12.96	2723	137	3.50	39	13	75	11	18	2.2	86	0.22	0.17	0.18	0.18
DB60	AIRPORT	DC	SWING	1-WAY	INT/VEST	95	6.91	2545	201	3.50	57	5	89	6	27	1.7	97	0.20	0.19	0.24	0.19
DB61	HOSP.	DC	SLIDE	2-WAY	INT/VEST	93	11.64	4215	218	4.00	55	2	79	18	7	2.1	114	0.29	0.22	0.26	0.23
DB62	HOSP.	DC	SLIDE	2-WAY	EXT/VEST	93	8.16	3124	229	3.50	65	3	91	6	3	1.8	117	0.25	0.22	0.27	0.23
DB63	MEDICAL	VA	SLIDE	2-WAY	INT/VEST	97	6.33	4241	295	3.75	79	13	74	13	3	3.0	233	0.31	0.39	0.38	0.41
DB64	MEDICAL	VA	SLIDE	2-WAY	INT/VEST	97	6.91	1712	152	3.10	49	5	85	10	8	1.5	74	0.15	0.15	0.19	0.15
DB65	MEDICAL	VA	SLIDE	2-WAY	INT/VEST	97	6.33	3036	227	3.10	73	15	79	6	1	2.9	210	0.27	0.36	0.33	0.37
DB66	MEDICAL	VA	SLIDE	2-WAY	INT/VEST	96	6.33	2563	174	3.50	50	15	75	9	3	3.1	153	0.20	0.28	0.25	0.29
DB67	MEDICAL	VA	SLIDE	2-WAY	INT/VEST	96	6.33	2097	139	2.75	51	17	72	10	1	3.2	164	0.21	0.30	0.25	0.31
DB68	HOSP.	PA	FOLD	2-WAY	EXT/VEST	89	8.11	2861	191	2.75	69	6	64	30	5	2.5	173	0.29	0.31	0.31	0.32

TABLE 1 (Continued)
Data and Analysis for Individual Cases

Observer	Type	Location (State)	Type of Door	Traffic Pattern	Door Configuration: Interior or exterior door with or without vestibule	Outside Temperature (°F)	Base Open Time (sec)	Open Time (sec) during observation period	Number of Uses	Hours of Data Collected	Uses per Hour	Percent Children	Percent Adult	Percent Elderly	Percent Cart	People per Use	People per Hour	Data Open Fraction—Uncorrected	Model Open Fraction—Uncorrected	Data Open Fraction—Base Open Time Corrected	Model Open Fraction—Base Open Time Corrected
DB69	HOSP.	PA	FOLD	2-WAY	INT/VEST	89	8.86	2151	148	2.50	59	6	70	24	3	2.2	130	0.24	0.24	0.25	0.25
DB70	HOSP.	PA	SLIDE	2-WAY	EXT/VEST	72	7.21	1417	105	3.00	35	9	64	26	4	1.9	66	0.13	0.13	0.15	0.14
DB71	RETAIL	PA	SLIDE	1-WAY	EXT/VEST	72	9.08	2342	186	4.25	44	12	73	15	13	1.4	60	0.15	0.12	0.16	0.12
MY1	HOTEL	Mb	SLIDE	2-WAY	INT/VEST	-8	4.80	1346	188	4.00	47	4	82	14	1	1.8	84	0.09	0.17	0.15	0.17
MY2	RETAIL	Mb	SWING	1-WAY	EXT/VEST	-15	9.88	626	62	4.00	16	0	96	4	0	1.1	17	0.04	0.04	0.04	0.04
MY3	RETAIL	Mb	SWING	1-WAY	EXT/INT	0	8.08	255	29	4.00	7	0	97	3	0	1.1	8	0.02	0.02	0.02	0.02
MY4	LIBRARY	Mb	SWING	2-WAY	INT/VEST	-21	9.52	3239	237	4.00	59	6	82	12	0	1.8	106	0.22	0.20	0.22	0.21
MY6	RETAIL	Mb	SWING	1-WAY	INT/VEST	11	8.18	3584	307	4.00	77	9	74	17	0	1.6	119	0.25	0.23	0.27	0.23
MY7	RETAIL	Mb	SWING	1-WAY	EXT/INT	1	9.04	993	97	4.00	24	3	82	16	0	1.1	27	0.07	0.06	0.07	0.06
MY9	AIRPORT	Mb	SLIDE	2-WAY	INT/VEST	23	6.88	594	72	4.00	18	10	82	9	0	1.3	23	0.04	0.05	0.05	0.05
MY10	RETAIL	Mb	SWING	1-WAY	EXT/VEST	21	8.78	1882	178	4.00	45	13	69	17	0	1.7	75	0.13	0.15	0.14	0.15
RH1	RETAIL	PA	SWING	1-WAY	EXT/VEST	46	7.29	2905	240	4.00	60	10	78	12	37	2.0	122	0.20	0.23	0.24	0.24
					Max.	**107**	**27.47**	**6628**	**406**	**8.00**	**164**	**32**	**100**	**48**	**37**	**7.7**	**441**	**0.62**	**0.61**	**0.67**	**0.63**
					Min.	**-21**	**4.74**	**255**	**29**	**0.50**	**7**	**0**	**38**	**0**	**0**	**1.1**	**8**	**0.02**	**0.02**	**0.02**	**0.02**
					Ave.	**72**	**9.37**	**2044**	**139**	**3.46**	**44**	**10**	**76**	**15**	**6**	**2.2**	**99**	**0.19**	**0.18**	**0.19**	**0.19**

TABLE 2
Data for Individual Cases

Building Type	State	Type of Door	Opening Time (sec)	Full Open Time (sec)	Closing Time (sec)	Vestibule Cases	
						Time Between Door Openings (sec)	Time Between Door Closings (sec)
Hotel	PA	Sliding	2.85	2.34	7.04	N/A	N/A
Hospital	PA	Sliding	2.42	2.21	3.44	2.23	2.98
Hospital	PA	Sliding	3.75	2.40	3.12	2.53	2.99
Retail	PA	Sliding	3.56	1.00	4.81	2.90	1.53
Retail	PA	Sliding	3.44	0.89	3.18	2.04	1.53
Retail	PA	Swinging	3.80	0.75	3.81	2.71	2.93
Retail	PA	Swinging	1.90	8.98	3.34	2.78	3.48
Medical	PA	Swinging	4.10	0.86	3.25	2.74	2.87
Medical	PA	Swinging	3.50	0.81	4.15	2.90	2.37
Medical	PA	Sliding	2.75	0.90	4.13	4.23	2.74
Medical	PA	Sliding	3.90	0.90	3.74	2.56	3.91
Medical	PA	Sliding	5.31	0.74	7.37	N/A	N/A
Retail	PA	Sliding	3.40	0.00	4.39	2.34	2.78
Retail	PA	Sliding	2.32	0.00	3.86	4.03	1.87
Retail	PA	Sliding	2.10	2.58	2.69	N/A	N/A
	Averaged Results:		**3.27**	**1.69**	**4.15**	**2.83**	**2.67**

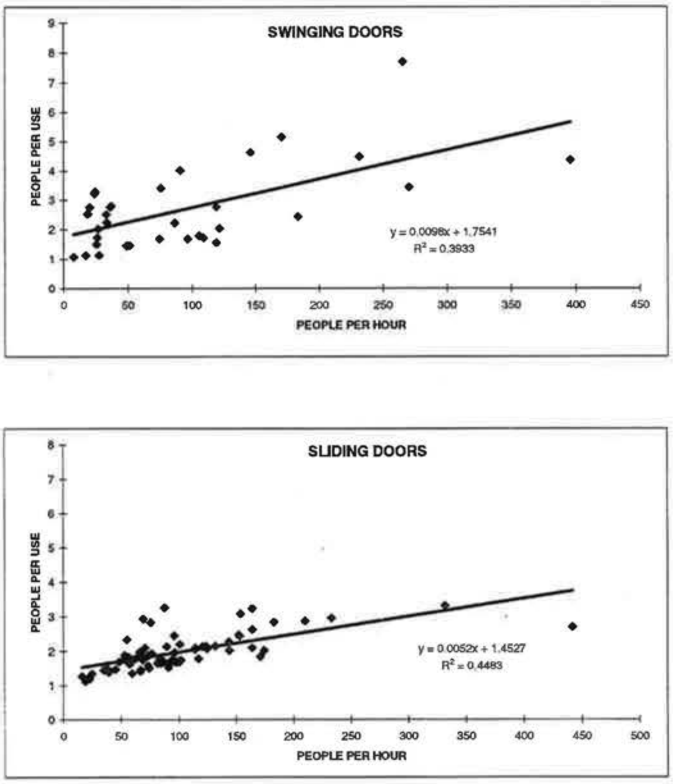

Figure 2 *People per use as a function of people per hour.*

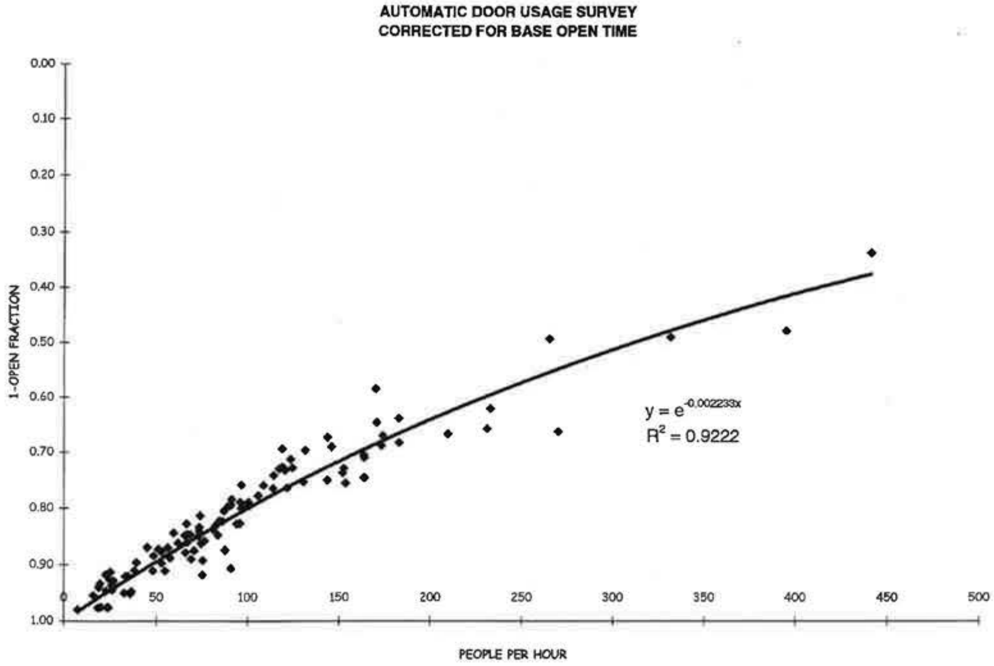

Figure 3 *Automatic door usage survey corrected for base open time.*

Definition of Terms and Basic Equations

The following terms and equations were used in this analysis:

a	= door opening time
b	= fully open time = $T_u - a - c - d$
c	= closing time from fully open to gap
d	= closing time from gap to fully closed
P_h	= people per hour
P_u	= people per use = $0.0052 \cdot P_h + 1.4527$ (sliding doors) and $0.0098 \cdot P_h + 1.7541$ (swinging doors)
T_h	= fractional time open = $1 - \exp(-0.002233 \cdot P_h)$ (single door)
T_h	= $(1 - \exp(-0.002233 \cdot P_h)) - 0.00041 \cdot U_h$ (vestibules)
U_h	= uses per hour = P_h / P_u
T_u	= time per use = T_h / U_h
F_o	= fraction open = $(a/2 + b + c\,(1 + g/w)/2 + dg/2w)/(a + b + c + d)$
g/w	= ratio of the closing gap after closing time c to the width of the fully open door

Analysis Neglecting the Effects of People in the Doorways

This analysis was first done without considering the effects of having a person in the doorway while still considering the open times that would result from having different numbers of people moving through the doors.

Door Schematic Based on Opening and Closing Times of a Single Door. The schematic in Figure 4 was used to model the opening and closing of a single door; a, b, c, and d represent the times as indicated above:

Each time period (a, b, c, and d) has a corresponding discharge coefficient (C_D) that is the average over the range of openness of that time period. The width (w) corresponds to the fully open condition and the gap (g) indicates the portion of the door still open when the closing speed slows down at the end of the closure of the door. For the case of a vestibule, two such drawings are superimposed on each other according to the lag time between when the first door opens and when the second door opens. This creates additional sections based on the openness of each door. Only the times during which both doors are at least partially open are included in the total open time. Under these conditions, the variables a, b, c, and d are based on the opening time of the outer door, the new fully open time when both doors are completely open, and the closing times of the inner door. Door schematics for vestibule cases will be shown later when vestibules are discussed further.

Average Discharge Coefficient. The measured discharge coefficients (C_{Dav}), which are based on the fully open area of the door, change with the openness of the door. Therefore, a time-averaged discharge coefficient (C_{Dav}) was calculated for each door to find the airflow through the door. This average was found for each case by first calculating the coefficients corresponding to each section of the open time. Next, these coefficients were multiplied by the time spans of the corresponding sections and the sum of these products was

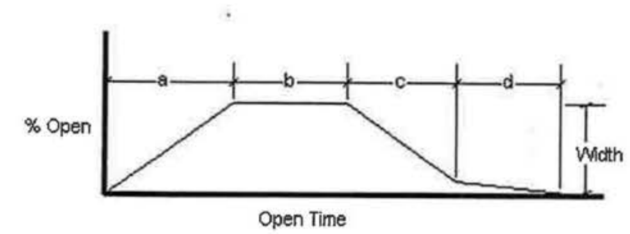

Figure 4 Percent open vs. time, single doors.

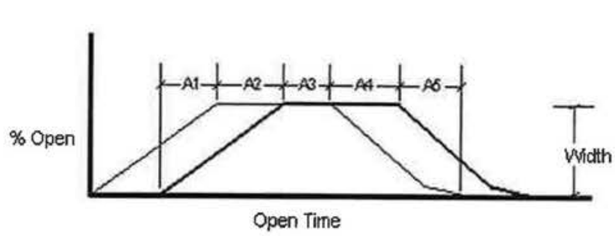

Figure 5 Percent open vs. time, swinging doors in vestibules.

found. This sum was then divided by the total open time. The following is the resulting equation for the average discharge coefficient of a swinging door with no vestibule:

$$C_{Dav} = (C_{Da} \cdot a + C_{Db} \cdot b + C_{Dc} \cdot c + C_{Dd} \cdot d)/(a + b + c + d) \quad (7)$$

where

C_{Da} = discharge coefficient for section *a*,

C_{Db} = discharge coefficient for section *b*,

C_{Dc} = discharge coefficient for section *c*,

C_{Dd} = discharge coefficient for section *d*.

A similar approach was used to find C_{Dav} of the vestibule cases.

The next step was to find the C_D values corresponding to each section of Figure 4, which are required in the above equation. This was done separately for each of the following cases.

Sliding Doors. For sliding doors with no vestibules, C_D was not measured based on a constant area but rather on the actual open area of the door. Therefore, C_D is constant and approximately equal to the value for an orifice. To account for the changes in openness in calculating the air flow, an average fraction open F_o was determined using the equation above. The air flow was then proportional to the constant measured C_D value of 0.6 multiplied by the calculated fraction open.

Swinging Doors. Both single and double swinging doors were considered in this analysis. In these cases, individual C_D values needed to be determined for sections *a*, *b*, *c*, and *d*. In order to find these values, an equation for C_D as a function of the open angle θ was found from the measured values of C_D (Yuill 1999). The equation for single doors was

$$C_D = 0.01344 \times \theta - 7.0635 \times 10^{-5} \times \theta^2 \quad (8)$$

where θ is the open angle in degrees.

For double doors:

$$C_D = 0.0016423 \times \theta + 1.5953 \times 10^{-4} \times \theta^2 - 1.1111 \times 10^{-6} \times \theta^3 \quad (9)$$

where θ is the open angle in degrees.

These equations were then integrated over the range of open angles for each section to get the average C_D values for each section.

Vestibules. The determination of the discharge coefficients for each part of the open time for vestibules was complicated by the fact that these values were dependent on the openness of both the inner and outer doors of the vestibule. Therefore, the equations relating C_D to door position were found using fourth-order regression against two variables, the open angles of the inner and outer doors. Equations for each of the 11 vestibule configurations studied are presented by Yuill (1999). For swinging doors these equations depended on the open angles of each door, and for sliding doors they were dependent on the fraction open of each door. As before, these equations were integrated to find the average C_D values for each section of open time. The number of sections needed for each case was dependent on the time between the opening of the inner door and the outer door and the time between the closing of the inner door and the outer door. For all vestibules studied, the average times between openings and between closings were taken to be 2.83 s and 2.67 s, respectively, based on measured data. The fully open time per use for both doors (A3 in Figure 6) was taken as the fully open time for one door minus the average of the opening lag time (A2 in Figure 6) and closing lag time (A4 + A5 in Figure 6).

Swinging Doors in Vestibules: Eight cases of swinging doors with vestibules were considered here. These included cases with two sets of double doors, two single doors directly across from one another, single doors diagonal to one another, single doors across from each other and opening inward (for all other cases the doors opened outward), one single and one double door across from each other, and cases with one single and one double door with the outer door located on the side of the vestibule.

For each type of vestibule described, the opening, fully open, and closing times were the same when the same number of people were passing through per hour. Each open time was broken down into seven sections, as shown by the schematic in Figure 5.

The C_D equations for each case were integrated with two sets of limits over each indicated section to find the average C_D values of each section.

Sliding Doors in Vestibules: Three cases of sliding doors with vestibules were studied, including one case with sliding doors across from each other and two cases with the outer door located on the side of the vestibule. For sliding doors, the closing times were such that only five sections were needed to describe the total open time, as shown in Figure 6.

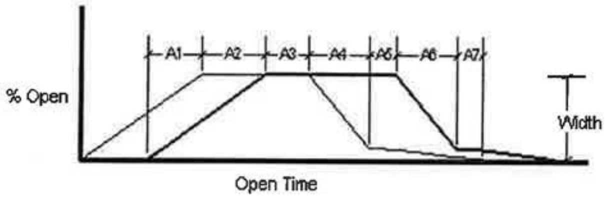

Figure 6 Percent open vs. time, sliding doors in vestibules.

As was done for swinging doors, the CD equations for each case were integrated with two sets of limits over each indicated section to find the average CD values of each section.

Results. The results indicate that air leakage through doorways is significantly reduced by the addition of a vestibule, even if both the inner and outer doors are open at the same time. These results also indicated that placing one set of doors on the side of the vestibule instead of straight across from the other set of doors lowers the air leakage through the vestibule. Figure 1 shows that an average reduction in airflow of about 30% results from the use of vestibules.

It was found that the difference in the results between double and single swinging doors for the cases with no vestibules was relatively small. Therefore, these results were combined for the final summary. In addition there were a number of swinging and sliding door cases with vestibules for which the results were also similar. These results were combined as well. Eventually the original fourteen cases studied were reduced to eight sets of results in the final summary. These results are presented in Table 3 and Figure 7.

Analysis Considering Effects of People in Doorways

The next step in this analysis was to consider the effects of people in the doorways on the C_D coefficients and therefore on the air flow through the doors.

Assumptions. For this analysis, three assumptions were made. First, it was assumed that each person would spend approximately one second in each doorway. Second, it was assumed that people would only pass through a doorway when the door was completely open. Finally, it was assumed that in the case of a vestibule, the C_D coefficients would only be affected by people in the doorways and not by people in the vestibule between the doors.

Cases for Which Data Were Available. In order to do this analysis, it was necessary to have measured C_D coefficients for people in individual doorways. These data were measured for single swinging doors opening outward and for sliding doors. This allowed the analysis of eight door configurations, including sliding doors with no vestibule, a single swinging door with no vestibule, a vestibule with single

TABLE 3
Averaged Summary of Airflow Coefficient vs. Number of People per Hour

		People per Hour													
		0	**10**	**20**	**30**	**40**	**50**	**75**	**100**	**200**	**250**	**300**	**350**	**400**	**450**
		Air Flow Coefficient $(cfm/(ft^2\ (in\ H_20)^{.5}))$													
1	Sliding doors no vestibule	0	33.7	67.4	101	135	168	251	332	629	760	879	987	1084	1172
2	Swinging doors no vestibule	0	37.1	74.7	113	151	189	284	376	716	865	1000	1122	1232	1331
	Swinging doors with vestibule														
3	Inner and outer doors same size opening out outer door across from inner door	0	22.5	46.1	70	95	121	185	249	492	601	700	790	872	945
4	Inner and outer doors same size opening in outer door across from inner door	0	28.6	58.8	90	123	156	240	325	649	794	928	1049	1159	1258
5	Double inner, single outer opening out outer door across from inner door	0	27.8	56.9	87	118	149	229	310	614	750	874	987	1090	1182
6	Single inner, double outer opening out outer door on left side of vestibule	0	13.6	27.8	43	58	73	111	150	296	361	420	474	523	567
	Sliding doors with vestibule														
7	Outer door across from inner door	0	29.1	58.9	89	120	150	228	304	595	726	845	955	1054	1143
8	Outer door on side of vestibule	0	22.4	45.1	68	91	115	172	229	442	537	624	703	775	839

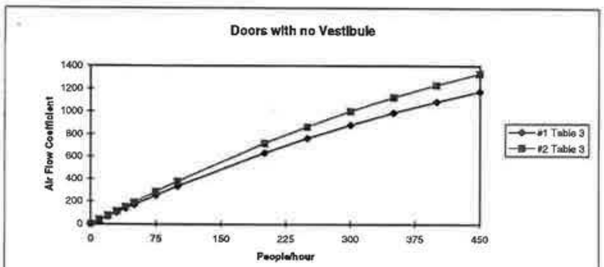

Figure 7 *Averaged summary graphs.*

swinging doors straight across from each other, two cases with single swinging doors at diagonals to each other, a vestibule with sliding doors straight across from each other, and two cases of vestibules with sliding doors, the outside door being located on the side of the vestibule. Cases with double swinging doors, single and double swinging doors together, or doors opening inward were not considered in this analysis.

Cases with No Vestibules. Cases with no vestibule were relatively simple. The procedure was the same as before, but the product of discharge coefficient and open time for this period was given by

$$C_D \times b = C_{DO} \times (b - P_u) + C_{DP} \times P_u \qquad (10)$$

where

C_{DO} = discharge coefficient for a fully open door,

b = fully open period (s),

P_u = number of people per use, and

C_{DP} = discharge coefficient for a single door with a person.

This product was then added to the other products of open times and C_D coefficients when calculating C_{Dav}

Cases with Vestibules. In order to find the C_D values for cases with vestibules, it was necessary to know the C_D values of each individual door and then find the overall C_D according to Equations 1 and 2. C_v in Equation 2 is a correction factor that accounts for the flow pattern in the vestibule, which causes the actual measured coefficient to be different from the ideal coefficients. For this analysis, the C_v coefficients used were the average of all of the measured C_v coefficients without people for each case.

It was necessary to consider three situations: the inner door completely open while the outer door is opening, both doors completely open, and the outer door completely open while the inner door is closing. Therefore, it was necessary to consider the value of C_D with a person in the fully open door for both sliding and swinging doors and the average C_D during opening and closing times for both types of doors.

Average C_D *for One Door Fully Open*: Since people are randomly in and out of the doorway when it is completely open, the C_D coefficient is not constant over the fully open time. An average C_D coefficient during the fully open time, C_{DO}, was found by smoothing out the effects of people over the entire period. The averaged coefficient was

$$C_{DO} = C_{DNP} - (C_{DNP} - C_{DWP}) \cdot (P_u \cdot T_P / b_1) \qquad (11)$$

where

C_{DO}. = average flow coefficient when the door is open and people are passing through,

C_{DNP} = flow coefficient of the open door when no people are moving through,

C_{DWP} = flow coefficient of the open door when a person is in the doorway,

P_u = people per use,

T_p = time for a person to pass through a doorway (assumed to be 1 s),

b_1 = fully open time for one door alone.

In this way the effects of people were averaged out over the entire fully open time.

Average C_D *for an Opening or Closing Door:* When a door is opening or closing, it is assumed that there are no people in the doorway so it was only necessary to find the average C_D value for each time period with no people. Also, it was only necessary to do this for time periods when the other door was completely open, since only then was there a person in the other door. The analysis above, "Analysis Neglecting the Effects of People in the Doorways," could be applied to the remaining time periods.

Swinging Doors: For swinging doors, the average coefficients were found by integrating the C_D equation for a single swinging door over the limits of the open angle θ for each time period in question.

Sliding Doors: For sliding doors, the average coefficients were found by multiplying the area under the curve for each

TABLE 4
Averaged Summary of Airflow Coefficient Corrected for the Presence of a Person vs. Number of People per Hour

		People per Hour													
		0	**10**	**20**	**30**	**40**	**50**	**75**	**100**	**200**	**250**	**300**	**350**	**400**	**450**
		Air Flow Coefficient (cfm/(ft^2 (in H$_2$0)$^{.5}$))													
1	Sliding doors no vestibule	0	32.5	65.9	99	132	164	245	324	613	739	853	956	1048	1131
2	Swinging doors no vestibule	0	37.8	76	114	153	191	285	378	712	856	987	1104	1208	1301
3	Swinging doors with vestibule	0	22.5	45.8	70	94	119	181	243	475	578	671	755	831	898
	Sliding doors with vestibule														
4	Outer door across from inner door	0	21	42.5	64	87	109	166	222	437	533	622	702	774	839
5	Outer door left side of vestibule	0	18.9	38.3	58	78	99	149	200	393	480	559	631	695	754

TABLE 5
Condensed Summary of Airflow Coefficient Corrected for the Presence of a Person vs. Number of People per Hour

	People per Hour													
	0	**10**	**20**	**30**	**40**	**50**	**75**	**100**	**200**	**250**	**300**	**350**	**400**	**450**
	Air Flow Coefficient (cfm/(ft^2 (in H$_2$0)$^{.5}$))													
Doors no vestibule	0	35.2	71	107	143	178	265	351	663	798	920	1030	1128	1216
Doors with vestibule	0	21.1	43	65	88	111	168	225	441	538	626	705	776	840

time period (which corresponds to the fraction open for that time period) by the constant C_D of 0.6 measured for the sliding door.

Once determined, these C_D values for individual doors were used in Equations 1 and 2 to find the overall C_D for each time period. The C_Ds for sections where both doors are partially closed were the same as those calculated when the effects of people were neglected, as it is assumed that people are only in the doorways when they are fully open.

Once the C_Ds for each time period were determined, C_{Dav} was found for each case, as in the previous analysis in which people were not considered.

Summary of the Results Obtained by Correcting for People. When the effects of people were considered, it was found that the original eight cases could be reduced to five due to similarities in results. For simplicity these results were combined further to produce two summary cases, one for doors without vestibules and one for doors with vestibules. See Tables 4 and 5 as well as Figures 1 and 8 for these summarized results. Yuill (1999) presents the results of each individual case studied in this portion of the analysis and the summary of these results.

DISCUSSION

The objective of this project was to develop a method that could be used by designers to estimate the air leakage through automatic doors. The application of these estimates would be in estimating the heating and cooling loads resulting from this air leakage. It was desired to keep the method simple. Furthermore, it was recognized that designers do not have accurate

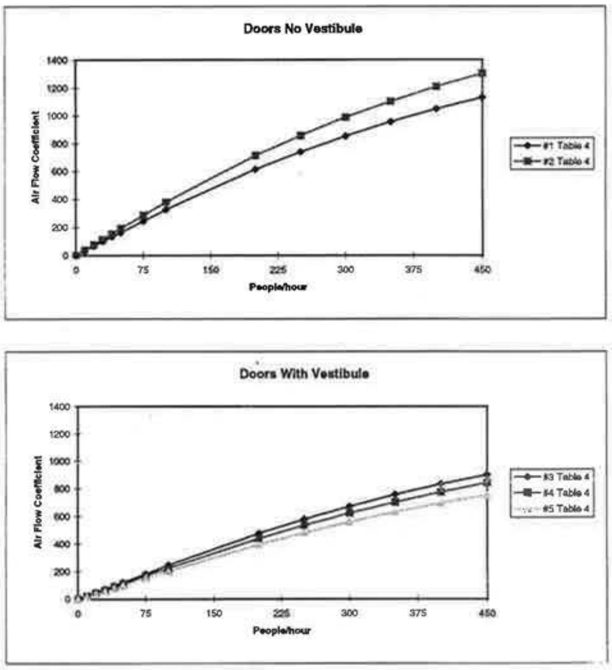

Figure 8 *Summary of graphs corrected for the presence of a person.*

data about the usage rates of automatic doors or about the timing of the opening and closing of these doors. Therefore, the results obtained have been reduced to two graphs, for doors with and without vestibules. This introduces errors of approximately 7% in several cases and up to 10% in one case. However, this simplification was believed to be justified by the reduction in the designer's effort, especially considering the uncertainties in the input data used by the designer.

Only one vestibule size (2.743 m deep and 3.658 m wide [9 ft deep and 12 ft wide]) was used to develop the flow coefficients for the vestibules. It is probable that different vestibule sizes and configurations would yield different results. For example, a very small vestibule, only slightly wider than the door, with sliding doors at both ends, would likely have a discharge coefficient near to that of a single door, 0.6, rather than the value of 0.49 recorded in the present study for a larger vestibule. On the other hand, a very large vestibule would allow the velocity of the air flowing through the first door to be completely dissipated, and the discharge coefficient would approach the ideal value of 0.31 for a pair of doors in series. This range of possible values indicates that further measurements of different vestibule sizes and configurations would be justified.

The discharge coefficients for vestibules with side entrances were significantly lower than for vestibules with front entrances. For the reasons discussed above, the simplified summary graph, (Figure 1) does not show this effect, but it can be seen in Table 3 and Figure 7 for doors with no people in them.

Designers who wish to apply the results presented here may find a set of sample design calculations useful. Such a set of calculations is presented in the final report on ASHRAE Research Project 763 (Yuill 1999). These example calculations will also appear in the next edition of *ASHRAE Fundamentals*.

Because of space limitations, the intermediate data on the discharge coefficients of doors have not been presented in this paper. This information may be useful in other applications, including the analysis of airflow within buildings. These data are available in the final report of ASHRAE Research Project 763 (Yuill 1999).

CONCLUSIONS

In this project, a study of the flow coefficients through doors with a range of different geometries was combined with a study of the patterns of usage of automatic doors. The result is an overall flow coefficient that need only be multiplied by the door area and by the indoor-outdoor pressure difference to determine the hourly airflow rate through the door. This overall flow coefficient is presented as a function of the door type and the hourly rate of use.

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