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Howard J. Cohen
University of Massachusetts Amherst

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PEDESTRIANS AND WIND IN THE URBAN ENVIRONMENT

A Dissertation Presented

By

HOWARD J. COHEN

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Psychology

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Approved as to style and content by:

Ronnie Janoff-Bulman

Stanley Moss, Chairperson of Committee

Howard Gadlin, Member

Ronnie Janoff-Bulman, Member

Hugh Davis, Member

Bonnie R. Strickland

Bonnie R. Strickland, Chairperson
Department of Psychology

ABSTRACT

Pedestrians and Wind in the Urban Environment

September, 1980

Howard J. Cohen, B.S., University of Illinois
M.S., Ph.D., University of Massachusetts
Directed by: Professor Stanley Moss

In recent years the problem of extreme winds in and around tall buildings has drawn increasing public attention. Spectacular wind problems have occurred at new high-rise buildings in New York, Chicago, and Boston, for example. Although wind-tunnel experiments have determined that tall buildings can cause ground-level wind speeds that are two to three times faster than ambient speeds, no study has examined the effects of these conditions on pedestrian behavior in an urban environment. Obviously, these accelerated winds can drastically affect pedestrian behavior and cause great inconvenience to those people negotiating doors, steps, walkways, or simply going about their daily activities. The intent of this study is to document some of these effects on pedestrian behavior. Four sites were selected in the city of Boston: the sidewalk adjacent to a 500-foot building; the entrance walkway to a 600-foot office building; the public plaza adjoining Boston City Hall; and a sitting and strolling area on the Boston Common, a large public park. Behavioral and wind-speed data were collected for winter, spring, and summer during a baseline (ambient wind speed less than 10 mph) and a test day (ambient wind speed greater than 20 mph). Pedestrian behavior was analyzed utilizing 8 mm time-lapse films (2/3 sec/frame). Through an adaptation of behavioral mapping techniques, a perspective grid was developed and superimposed on the projected films, enabling a direct correlation of onsite wind conditions with pedestrian behavior. In addition, questionnaire data was collected for each of three sections of the instrument: semantic differentials, attitude statements, and self-reports on behavioral responses. Finally, consumer data was collected on the number of cash-register transactions, supplied by businesses adjacent to two of the study sites. The results showed that for each site within each season, pedestrian density was significantly lower on windy days than on baseline days. Furthermore, group circulation patterns based on a high-probability path model were significantly less varied and diffuse on test days as compared to baseline days. Paths were more randomly distributed on baseline days whereas on windy days the paths showed more directionality. In addition, within all seasons for all sites, test days resulted in a significant increase in speed of pedestrian movement, significantly less pairings among pedestrians, and significantly lower levels of other types of pedestrian behavior.

The questionnaire and consumer data, when analyzed in conjunction with the pedestrian path and density data, confirmed these results.

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CHAPTER I

INTRODUCTION

Overview

In recent years the problem of extreme wind conditions in and around tall buildings has drawn increasing public attention and concern. In major cities throughout the United States spectacular wind problems have occurred at new high-rise buildings. In some instances the wind speeds have caused personal injuries as pedestrians have been literally blown off their feet. Nonetheless, major research has emphasized only structural and surface problems of these buildings. Although wind-tunnel experiments have conclusively determined that high-rise buildings caused ground-level wind speeds two to three times faster than ambient speeds, no study has examined the effects of these conditions on pedestrian behavior (Pushkavev and Zupan, 1975). Clearly, these accelerated wind speeds can drastically affect pedestrian movement and behavior and can cause great inconvenience to those people negotiating doors, steps, walkways, or simply going about their daily activities. The intent of this study is to document some of these effects on pedestrian movement in a variety of settings in an urban environment. This thesis is based upon a two-year study which was funded by the National Science Foundation (NSF Grant ENG 75-04353 and ENG 76-23713) and was a cooperative effort between the Institute for Man and the Environment (University of Massachusetts) and Weather Dynamics, Inc., of Arlington, Massachusetts.

This study consisted of the acquisition of the following types of behavioral data: (1) 8 mm time lapse films of pedestrian movement; (2) questionnaire data measuring attitudes and perceptional responses to various wind speeds; and (3) consumer information on the number of cash-register transactions at various businesses adjacent to the study areas. These behavioral measures were compiled under various experimental conditions.

The behavioral and wind speed data were collected for three different seasons: winter (December 21-March 21), spring (March 21-June 21), and ummer (June 21-September 21). For each season data was collected for two days: (1) a baseline day on which the ambient wind speed measured at Logan Airport was less than or equal to 10 mph (4.5 m/sec); and (2) a test day on which the ambient wind speed measured at Logan was greater than or equal to 20 mph (9.1 m/sec).

On-Site Behavioral Data Acquisition.

Simultaneous with the wind-data acquisition, 8 mm time-lapse films (2/3 sec per frame) were taken of the four study sites. Through an adaptation of behavioral mapping techniques, a perspective grid was developed and superimposed on the projected films, enabling a direct correlation of on-site wind conditions with pedestrian behavior. The behavioral map of each site was analyzed to determine:

1. individual path movement through the behavioral map
2. density of pedestrians
3. interpersonal distance and orientation
4. gross body movement
5. aggregate circulation patterns
6. speed of pedestrian movement
7. individual pedestrian behaviors (sitting, talking, eating lunch, etc.)

Concurrently with the unobtrusive film technique, a questionnaire was developed to test individual attitudes and perceptions on several behavioral scales. The survey was administered to random populations drawn from the principal office buildings in each of two designated sites. Semantic differentials were used to test individual perceptions of the four sites depicted in black and white photographs. A second section, consisting of an attitude survey, was employed to evaluate opinions concerning the effects of wind conditions on behavior. A final section explored behavioral responses to various wind conditions by ascertaining whether subjects change or postpone everyday activities such as running errands or going outside of the building during lunch because of wind/weather conditions.

As a supplement to observational data from the unobtrusive films and the questionnaire, restaurants and shops within the general study area were solicited for receipt information (i.e., number of cash-register transactions per day). Several businesses provided daily receipt information which affords a detailed evaluation of the relationship between the wind and consumer activity. All consumer-receipt data are correlated with weather data from the National Weather Service local climatological records as well as with on-site wind measurements.

On-Site Data Acquisition.

Measurements of on-site wind conditions were made using a Disa hot-wire anemometer system. Output data was collected on an analogue tape subsequent to computer processing. The on-site instrumentation was mobile and easily relocated from site to site. The purpose of the on-site wind data was to qualitatively describe the transient characteristics of wind that cause problems for pedestrians. Spatial and temporal variations were recorded at all sites. All of these sites were known areas where pedestrians were frequently subjected to unpleasant and dangerous wind conditions.

Study-Site Selection.

Four study sites were selected in the city of Boston, which has one of the highest average wind speeds for an urban area in this country. Criteria for selection included:

(1) suitability for anticipated wind conditions;

(2) suitability for location of wind-measuring instrumentation without disrupting pedestrian traffic in the vicinity;

(3) availability of nearby sites for camera crews to make observational records; and

(4) cooperation of owners/managers from buildings adjacent to the test site.

The four sites that were finally selected are:

(a) the sidewalk area adjacent to a 500-foot (152-meter) building where it is generally recognized that unpleasant wind conditions frequently occur;

(b) the entrance walkway to a 600-foot (183-meter) office building where dangerously fast winds are known to occur;

(c) on the public plaza adjoining City Hall in Boston; and

(d) a sitting and strolling area on the Boston Common, a large public park.

Analysis

Movie-Film Data.

The films of each site were projected on a two-point perspective grid map of each site depicting buildings and related features. Therefore, each site had its own distance grid map corresponding to the various structures of each area as well as various filming restrictions, such as camera height, angle, and filming distance. Two basic approaches were employed in the analysis of each film. First, sequential path analysis of pedestrians were executed by frame-by-frame plotting of randomly selected subjects. As frames were advanced the pedestrian's position was recorded on the perspective grid map and map coordinates of each subject's position was catalogued on data sheets. This dual procedure enabled a pictorial representation of paths to be transferred directly onto the grid map and provided in a form suitable for statistical analysis. A second set of grid maps were utilized to determine the population density of each site.

These two initial approaches to the analysis of the films provided data relative to variability in pedestrian density, pattern of density on the behavioral map, speed of movement, individual paths, and macro-circulation patterns under varying wind conditions and at different seasons of the year. Subsequent observational analysis focused on gross body movement and orientation, interpersonal distance among aggregates, and pedestrian behaviors.

Questionnaire Data.

Questionnaire data were analyzed to identify significant differences between the two populations for each of three sections of the instrument: semantic differentials, attitude statements, and self-reports on behavioral responses. The data were also analyzed for significant differences between baseline and test days.

Consumer/Economic Data.

Information on the number of cash-register transactions, supplied by businesses adjacent to two of the study sites, was analyzed for significant correlations with ambient wind speeds reported by the Logan Airport Weather Station. The data was also analyzed for differences between baseline and test days.

Thesis Format.

This dissertation is presented in five chapters. The first chapter has presented a general overview of the thesis. Chapter 2 reviews the pertinent literature for several research areas: (1) pedestrian movement studies, (2) wind-pedestrian interactions, and (3) transitional probability analysis of aggregate pedestrian path movement. Chapter 3 describes in detail the methods of data collection and analysis, instrumentation, and site selection. Particular emphasis is given to detailed analysis of the logic involved in the path and walk Fortran programs which are used to generate the path models (highest probability paths) employed in this study. In addition, the fully documented

Fortran programs are provided for each of the two methodological innovations. Chapter 4 presents the analysis of all behavioral data. This chapter is divided into four subsections. In the first section, the high-probability path results are presented for each site. Included in this section are the velocity, density, and behavioral measures developed from the behavioral map. The films of pedestrian movement and behavior at each site are analyzed and evaluated separately. This procedure ensures that the specific characteristics of each of these urban areas can be evaluated relative to the particular wind configurations in each space. In the second section the wind contour behavioral maps are analyzed. This provides the opportunity to examine the relationship between two types of modeling; that is, the relationship between the highest probability path model as it covaries with the wind contour model. The relationship of these two models allows one to predict the environmental consequences of specific wind speeds and their direction. Section 3 analyzes all aspects of the questionnaire, particularly the semantic differentials and the attitudinal survey. The final section examines the consumer data which was collected. Finally, Chapter 5 discusses the results and the interrelationships between the different behavioral measures.

CHAPTER II

LITERATURE REVIEW

Wind Speed Effects and Criteria.

In major cities the construction of high-rise buildings has resulted in many unanticipated problems. Particularly troublesome has been the problem of extreme winds in and around tall buildings. Spectacular wind problems have occurred at new high-rise buildings in New York, Chicago, and Boston. Although architects and planners have devoted considerable time and effort to research investigating the structural and surface or window problems of tall buildings, the effects of accelerated ground-level wind speeds have been ignored for the most part. Architects concerned with the design and planning of tall buildings have to know whether high wind speeds are likely to occur at ground level, but the more difficult problem of assessing whether the predicted wind conditions are acceptable to pedestrians walking within the vicinity has not been part of their calculations. Though wind tunnel experiments have determined that tall buildings can cause ground-level wind speeds that are two or three times faster than ambient speeds, no study has examined the effects of these conditions on pedestrians (Pushkavev and Zupan, 1975).

Obviously, these accelerated winds can drastically affect pedestrian behavior and cause great inconvenience to those people negotiating doors, steps, walkways, or simply going about their daily activities. Previous research into the effect of wind upon people, however, has concentrated on the effects of wind as a cooling agent (Penwarden, 1973). Studies have demonstrated that a cold wind rapidly cools exposed fingers reducing manual dexterity and makes the fingers numb (Mackworth, 1953). Likewise, a cold wind makes the eyes water, reducing visual acuity (Kobrick, 1965). Pugh also conducted studies on the effects of wind on the metabolic rate of individuals while walking in the wind (Pugh, 1971). Utilizing these results he suggested criteria for determining wind comfort under various climatic conditions.

The earliest systematic studies on the effects of wind was by Francis Beaufort, whose scale of wind force devised in 1806, is still used today. Designed originally for wind speed at sea, it has been extended and revised for estimating wind speeds on land. Table 1 lists Beaufort numbers and wind speed ranges.

The problem with Beaufort's scale for experimental purposes is that the scale is based on casual observations of the effects of wind speed. Rather than being based on objective assessments of mechanical effects of wind speed, the scale numbers were based on subjective reactions which could be influenced by other climatic factors.

Table 1

Summary of Wind Effect

Beaufort Number	Speed (m/sec)	Effects
0,1	0-1.5	Calm, no noticeable wind
2	1.6-3.3	Wind felt on face
3	3.4-5.4	Wind extends light flage, hair is disturbed, clothing flaps
4	5.5-7.9	Raises dust, dry soil and loose paper
5	8.0-10.7	Force of wind felt on body. Drifting snow becomes airborne. Limit of agreeable wind on land
6	10.8-13.8	Umbrellas used with difficulty. Hair blow straight. Difficult to walk steadily.
7	13.9-17.1	Inconvenience felt when walking
8	17.2-20.7	Generally impedes progress. Great difficulty with balance in gusts
9	20.8-24.4	People blown over by gusts

Moreover, Beaufort's scale and the other general methods utilized in these experiments suffered from several methodological defects. Hunt (1976) has argued that while these methods have measured the subjective assessments of different wind conditions these studies have failed to determine the following: (1) a measurement of subject performance in the completion of simple tasks; (2) a measurement of subject steadiness, their direction and the forces acting on them while walking in different wind conditions. To measure these two conditions which have often been overlooked by architects and planners, Hunt chose to simulate the most unpleasant aspects of wind conditions to be found around buildings and expose subjects to these conditions under controlled conditions. Specifically, Hunt simulated wind conditions by utilizing a complex wind tunnel which allowed volunteers limited maneuverability. In order to establish criteria for acceptable wind conditions, Hunt employed various wind conditions to determine under which wind conditions people's performance or subjective assessments begin to be reliably affected and how much stronger wind conditions must become before there is danger of overbalancing when either walking or performing simple tasks. Since Hunt's experiment is the most detailed effort to determine these factors, it will be examined in detail.

The experiment was organized in three parts. First each volunteer was tested and timed while performing various tasks and while walking. In addition, each subject had his subjective verbal assessment of the wind. Each subject experienced a single wind speed, once with turbulence and once without turbulence. In the second part, groups of subjects entered the wind tunnel and gave verbal assessments of the wind conditions for each of 20 conditions of wind speed and turbulence. In the third part each subject at each of a number of conditions walked up and down or across the wind tunnel over a force plate built into the floor of the wind tunnel. This allowed the experimenter to measure the forces on the floor by the feet of people walking in the tunnel.

In the first part of the experiment, where subjects performed a number of tasks and gave semantic assessments of the wind conditions, each subject was tested in one of two wind conditions. Each of these two wind speeds had one of two further conditions--with and without turbulence. The four experimental conditions are listed below.

Table 2

Summary of Hunt's Experimental Conditions

Condition	Mean Wind Speed	Turbulence
A	4 m/s	none
B	4 m/s	severe
C	8.5 m/s	none
D	8.5 m/s	severe

All subjects were women ranging in age from 28 to 59. During all experimental conditions, subjects wore outdoor clothing. Each subject experienced only one of the four wind conditions and performed one of the eight tasks. Although somewhat contrived and artificial, the tasks provided the experimenter with highly operationalized tasks which could be easily controlled. The following tasks were utilized:

(1) subjects walked into the wind tunnel on a board to which was fastened white paper. Inky pads had been tied to each subject's feet to make visible the footmarks, from which the subject's deflection was measured.

(2) subjects inked their feet soles and walked up and down the tunnel. This task differed from the first in that it was designed to assess the subject's control while walking in a steady and gusty wind.

(3) The time to put on a nylon raincoat measured over four trials.

(4) The time to put on a head scarf measured over four trials.

(5) The time to cross out selected words on a list.

(6) the subject was timed while locating the ringed word on a given page of newspaper.

(7) the subject, while seated at a table, had to fill a wine glass with water up to a mark 1.5 cm. The amount of water spilt was measured.

(8) Semantic assessments. In these tests the subjects had to put a mark on a series of lines. At each end of the line were words describing opposite assessment of the situation.

The results of this experiment showed that increasing the wind speed from 4 m/s to 8 m/s interfered significantly with the performance of many of the tasks. Increasing the gustiness or turbulence from a negligible level to that characteristic of a gusty wind also significantly interfered with the performance of the skilled tasks. For example, looking solely at the effect of an increase in wind speed and not of gustiness, the task of putting on the raincoat took significantly longer (20 sec to 26 sec), searching through the newspaper took significantly longer (30 sec to 36 sec), and subjects blinked more often (12 to 18 blinks per min). Independent of wind speed, gustiness/turbulence was found to significantly increase the time to put on a raincoat (by 10%), the time to tie on a head scarf (by 30%), and the amount of water that is spilt when pouring water from a bottle into a glass. For the tasks of tying on a head scarf and pouring water, an increase in wind speed from 4 to 8.5 m/s had no effect.

From an analysis of the tasks and a comparison of the difference in the effects on performance of increasing the mean wind speed and increasing the turbulence, Hunt concluded that mean wind speed usually has a more detrimental effect on performance than turbulence. The most striking finding about the effect of turbulence is that where it strongly affects performance, the effects are comparable in magnitude with the effects of doubling the mean wind speed even though the velocity fluctuations never ran more than 20% of the mean wind speed.

Out of the 13 semantic differentials only four produced significant results. Of the differentials which showed significant differences, all showed a more negative response with a wind speed level of 8.5 m/s than a wind speed of 4 m/s. However, no significant differences were found when the gustiness was increased.

In the final part of the experiment, Hunt measured the amount of deflection in walking when subjects entered the wind tunnel under varying wind conditions. First, it was found that when entering the tunnel at a wind speed of 8.5 m/s, a significant deflection occurs in the direction of walking by about 9 cm in 3 steps. In some instances this surprisingly large deflection could lead to a pedestrian slipping off the pavement or losing his balance. In fact in seven instances, subjects were momentarily blown off balance at a wind speed of 8.5 m/s (i.e., 21 mph). Two subjects (both over fifty years of age) were completely blown off balance when entering the wind tunnel. Again these results were surprising since it was customary to assume that people only lose their balance in the wind at average wind speeds (or gusts) at about 13-15 m/s (28.5-36 mph). Consequently, the conclusion could be drawn that in the common situation where wind speed changes suddenly near the corner of a building, there is considerable danger of accidents caused by high wind speeds. Another significant result of this analysis of walking and wind speed was that raising the wind speed from 4 to 8.5 m/s or increasing the gustiness at 4 m/s had no effect on deflection. However, adding gustiness to a wind speed of 8.5 m/s produced a significant increase (25% deflection) in the final width of the foot marks. This result agreed with the volunteers' assessment that they felt unbalanced when gustiness was added to an increase in wind speed.

These experiments showed that wind affects peoples' ability to perform simple tasks, how people subjectively assess the wind and its effects, and how the wind affects people's walking. The performance of everyday skilled tasks worsened as the wind increased from 4 to 8.5 m/s. In addition, the subjective assessment showed that above

6 m/s (15.5 mph) the wind becomes more noticeable and walking deflection becomes significantly greater. At 13 m/s (28.5 mph) walking becomes extremely difficult, particularly for the elderly who have a slower reaction time. This finding is based on the calculation that the peak wind force on the ground is double when walking into the wind and the peak sideways force is equal to the forward force when sideways to the wind. This conclusion is also based on Pugh's finding (1971) that oxygen and hence energy expenditure is doubled at this wind speed.

In other studies, Melbourne and Joubert (1971) in observing wind problems around a number of high-rise buildings in Australia found that a maximum gust of 23 m/s (51 mph) around a building in Australia literally brought people to their knees. Penwarden and Wise (1975) estimated that a wind with an average speed of 15 to 24 m/s (33 to 53 mph) gusting to 30 m/s (66 mph) was the cause of a fatal accident of a woman in England. Wind tunnel observations by Isyumov and Davenport (1975) showed that a steady uniform wind can be dangerous to some people at 20 m/s (44 mph) while other more sturdy types can cope with winds up to 30 m/s (66 mph). However, in nonuniform turbulent winds such as those usually encountered around high-rises, the safety standards proposed by Hunt et al. (1976) drops to 13 to 20 m/s (29 to 44 mph) with the caveat that even this level may be too high for the safety of elderly persons. Isyumov and Davenport's review of current research, however, points to 20 m/s as the threshold condition for physical danger.

On the basis of these observations, Davenport (1972) has suggested that areas where winds exceed Beaufort level 8 (52 mph, 19 m/s) on more than one occasion per year be regarded as dangerous to (and presumably unfit for) human use. Melbourne and Joubert (1971) on the other hand propose a slightly higher standard of 23 m/s (51 mph) once yearly as the acceptable level for wind. Criteria prepared by Penwarden and Wise (1975) are less rigid, but they nevertheless suggest that speeds of 15 to 20 m/s (33 to 44 mph) are likely to be dangerous.

Drawing on wind-tunnel observations by Hunt et al. as well as some earlier research, a number of comfort standards for wind conditions have also been proposed. These standards have tended over the years to differentiate comfort requirements for various activities. In 1971 Melbourne and Joubert suggested that if gust velocities in an area exceed 15 m/s (33 mph) for one percent of the total time, this should be regarded as unacceptable from the standpoint of user comfort. Lawson (1973) suggested that average speeds greater than Beaufort 4 (6.7 m/s, 15 mph) for one hour per day are acceptable, but that speeds greater than Beaufort 6 (12.7 m/s, 28 mph) for one-half hour per day are not acceptable. Criteria proposed by Hunt et al.

(1976), however, differentiate between acceptable levels for walking and other more sedentary activities, such as reading a newspaper or eating lunch. They suggest that for safe and sure walking gusts lasting from 5 to 10 seconds should not exceed 13 m/s (29 mph) more than one percent of the time. This translates to a mean hourly speed of 9 m/s (20 mph) for one percent of the time. On the other hand, for people to feel little discomfort in the wind the mean hourly wind speed should not exceed 5 m/s (11 mph) for 90 percent of the time. Penwarden and Wise (1975) found that developments where mean speeds exceeded 5 m/s (11 mph) more than 20 percent of the time were likely to result in remedial measures being taken and therefore suggested that level as a standard.

Davenport (1973) has proposed the most specific set of standards for wind comfort. His scheme recognizes four levels of outdoor activity: (1) sitting, (2) strolling and skating, (3) short exposure, standing and sitting, and (4) long exposure, standing and sitting. For each of these activities, a comfort standard is suggested along with acceptable weekly, monthly, and yearly levels for winds exceeding the limit. Thus, for strolling and skating, Davenport suggests that the Beaufort level 4 (15 mph) is the appropriate comfortable level. Tolerable conditions of Beaufort level 5 (21 mph) are permitted once weekly; unpleasant conditions of Beaufort level 6 (28 mph) are permitted once monthly; and dangerous conditions of Beaufort level 8 (42 mph) are permitted once yearly.

Man-Environment Relationships.

Although these extensive efforts into the question of wind behavior around high-rises has resulted in a somewhat more accurate understanding of the problem, most of these contributions have come through the use of wind-tunnel tests. Though wind tunnel investigations of human behavior can provide useful guidelines for determining critical limits of ground-level wind speeds, this approach cannot capture the holistic sense of the overall structures of pedestrian movement in a real world setting. In order to make an objective evaluation of certain aspects of pedestrian movement as it covaries with changing wind conditions, this paper will now turn to the research on pedestrian movement.

Since man himself is an integral part of the environment, it is difficult to isolate behavioral events from their designed environments and abstract a causal relationship between spatial variables and behavior. The behavioral effects one is attempting to measure in order to make predictions of behavior in designed environments are embedded in the context of the environment. Removing the behavioral pattern from the context in which it occurs violates the integrity of both. One of the first psychologists to recognize this relationship was R. G. Barker. In his Ecological Psychology: Concepts and Methods for Studying the Environment of Human Behavior, Barker described a psychological methodology which was based on observation and analysis of behavior as it occurs in its natural setting. Taking a page from animal ecologists, who for years had provided detailed and meticulous descriptions of causal relationships of animal behavior in its natural setting, Barker attempted to analyze behavioral settings into their constitutive elements and forces as they impinged on the determinants of behavioral patterns.

Barker divided the environment into a number of discrete and variable properties. First, there were physical forces. These force fields were determined by the layout and arrangement of physical artifacts. Primarily they hinder or impel behavior. Next in the hierarchy were social forces. These express themselves primarily in the form of organizational rules which are constitutive of social relationships. Codified behavioral norms, laws, rules, and customs exert a strong and complex influence on all behavior. Physiological processes are likewise a primary element of all behavioral patterns. Specifically, the biological processes are internal indicators of behavioral patterns. Perception, as a regulator of communication and social interaction, works through culturally encoded information to control all behavioral and communicational responses. Learning is utilized to conform behavior to the existing and appropriate behavior norms and customs. Discrimination or selective behavior allows individuals to adapt to new situations and respond accordingly, Utilizing these general conceptual categories as a theoretical foundation, behavioral settings are described through a very elaborate technique. Specifically, the methodology records the number of times a particular event occurs within a given time period, the duration of the event, the number of persons in the population, and the total number of hours per person engaged in the event.

Human Spatial Behavior.

Barker's ecological approach to behavior-environment relationships provides a broad framework for analysis. Nonetheless, its global approach is also one of its major weaknesses. Because of the ambiguity of the conceptual framework, the ecological model does not provide the appropriate methodological techniques for settings which are in constant and rapid flux. In complex settings, the attempt to capture every aspect of the environment simultaneously leads to an analysis which sacrifices specificity and precision for generality and ambiguity. Since this study is primarily interested in spatial behavior as it co-varies with wind speed, we will examine the research which has analyzed this concept.

In complex settings human spatial behavior can take various forms depending on whether it occurs with individuals or in aggregates. Among the variables which affect spatial behavior are psychological, cultural, physical, and psycho-physical variables. In general, the studies on spatial behavior can be grouped into one or more categories related to certain spatial categories such as dominance and territoriality (Esser, 1971), or privacy and personal space (Sommer, 1969). Categories are discrete and operationalized for the purposes of behavioral measurement and quantification. Examples of behavioral units of analysis include the following: (1) the number of aggressive and submissive acts in a Rhesus dominance hierarchy, (2) the frequency and use of specific locations, (3) the interpersonal distance of individuals in a group, (4) the number of pro-social contacts among individuals, and (5) psycho-physiological measures. In the typical study, groups are observed unobtrusively in a variety of experimental conditions. Usually a checklist of the designated behaviors is constructed and frequency counts of the various behaviors are calculated Quantification is usually limited to frequency counts and statistical analyses such as Chi square and T tests.

Most of the research on spatial behavior concerns stationary behavior. In a number of studies, Esser (1968, 1970) has observed and analyzed dominance and territoriality in emotionally disturbed individuals. He discovered that in all these groupings there was a well ordered dominance hierarchy. In these settings, Esser operationally defined dominance in terms of interpersonal distance and degree of personal control. Dominant individuals were those who controlled and defined space for others in the group. They had free access to the entire space and were the focal points for the attention of other individuals. Furthermore, other subjects monitored and regulated their behavior relative to the dominant individual. Therefore, over a period of experimental sessions the dominant individual maintained a consistent and inflexible behavioral profile whereas submissive individuals showed a profile which changed constantly depending on circumstances. Finally, the personal territories of dominant individuals were rarely intruded upon while the personal space of submissive individuals were difficult to even calculate because of its ambiguity.

Sommer (1966, 1969, 1970) has provided another paradigm concerned with the analysis of personal space and types of behavior associated with the acquisition and defense of personal space. In his various studies he has continually stressed the importance of maintaining individual distance from others in a group. He has defined four major determinants of spatial behavior. These elements include the task of a group member (cooperative or competitive action), personality characteristics, cultural and educational background, and the specific environmental characteristics of the setting. Utilizing these variables, Sommer found that people maintain certain similarities in spacing while engaged in conversation. He argues that in conversation as well as all human social relationships there may be certain limits to human spatial organization. These limits will be based on the fact that the arrangement of the sense organs for purposes of perception delimit certain generalizable principles for all human communication and organization. To some extent all physical environments must conform to these principles or the organization will be unsuccessful.

In Behavior in Public Spaces: Notes of the Social Organization of Space, Goffman argued that individuals will tend over time to cooperatively distribute and arrange themselves in the available space. For example, in investigating the act of conversation, he argued that it is necessary for talk lines to be kept visually open. When the seating arrangements are such that conversations are frequently interrupted, the results will be breakdown in the pattern of conversation. In this study, however, Goffman provided no experimental methodology which would be useful in examining spatial relationships.

Research which has examined personal space and crowding suggests that concepts of crowding are largely determined by cultural norms. Hall (1966) has termed the word proxemics to describe four principal categories of relationships among individuals in aggregates. These dimensions--intimate, personal, social, and public--determine zones of intensity and directions of involvement in groups. The relationship between these dimensions delineate the territorial boundaries and distances which are maintained among groups. Hall has shown that the space surrounding the individual varies with the cultural context. These proxemic distances are more or less constant for each culture and are expressed socially in norms of etiquette.

Pedestrian Behavior and Movement.

Most studies of pedestrian movement study the effect of moving crowds. These studies examine stationary behavior in various public settings. For example, Stilitz (1969, 1970) observed that waiting people during rush hours seek protection from moving crowds. According to Stilitz, pedestrians find shelters in the vicinity of columns, niches, and corners. This result was explained by Stilitz by the hypothesis that individuals adopt a course which will involve the least expenditure of effort.

Wolff (1970) observed that in crowded situations, pedestrians will exhibit cooperative behavior. Wolff examined primarily those movements which pedestrians make to avoid bumping into each other. He found that pedestrians unconsciously adopt sidewalk rules which calibrate spacing among pedestrians. Depending on the density of pedestrian traffic, walking style and relationships of space varied to maintain a constant interpersonal space. From these results Wolff suggested that rules for acceptable social behavior are followed voluntarily by most pedestrians to avoid conflict in situations of varying density. Consequently, the less space available the more cooperation among pedestrians. Wolff also utilized a method of unobtrusive movies to record his data. Through the analysis of these films, the pedestrian movement patterns could be investigated by analyzing the films frame by frame. This allowed the researcher to construct a spatial distribution of pedestrians using a map.

The work of Dietrich Garbrecht (1969, 1970, 1971, 1973) will provide the theoretical framework for the pedestrian path model employed in this dissertation. Garbrecht has been one of the only researchers who has moved beyond the one dimensional descriptive analysis of pedestrian movement. Instead of basing his work on frequency counts, Garbrecht has developed a series of mathemetical models to describe pedestrian movement in a street grid. Since his work is the only similar attempt to employ stochastic modeling efforts to pedestrian movement, Garbrecht's various models will be examined in detail.

The Binomial Model of Pedestrian Movement.

Garbrecht's first approach (1969) utilized a binomial model to examine path selection and distribution of pedestrians over street networks. The analysis is not concerned with the manner in which an individual behaves when walking through a street corner, but with *aggregates* of pedestrians. The assumptions of this model are not based on experimental data but on arbitrary assumptions chosen by the experimenter. However, the model's framework is guided by three assumptions: (1) that the assumptions are consistent with the mathematical rules of the binomial distribution; (2) that they approximately represent the rules which describe path selection by pedestrians; and (3) that they be stated as simply as possible so that functional aspects can be explored in detail.

One aspect of pedestrian environments is that pedestrians walk from an object at origin O, say an office building, to an object at destination D, a store or restaurant. For purposes of the model, all origins and destinations are assumed to be at street intersections. The same facility or intersection may be an origin (O) and a destination (D) for the same person at a different point in time. For example, someone may walk from his house O to a friend's apartment D. He leaves his apartment O and goes to a restaurant D. He walks from the restaurant O and goes to bank D. Hence the restaurant, the bank, and the apartment are called O-D paths.

The intersections are connected by links, which are street sections one block in length. These links and intersections constitute a rectangular grid, which is determined by an origin O and a destination D such that the boundaries of the grid are the streets going through O and D. A grid consists of all paths from O to D satisfying two conditions: (1) that the paths are selected by using links of the grid; and (2) that paths are chosen from those minimizing time-distance (i.e., paths are equally long).

There are four additional assumptions concerning the pedestrians. First, trips are completely pedestrian (i.e., no transportation means is used during the trip). Second, pedestrian's time-distance is minimized. This assumption limits the analysis to a grid that is bounded by the streets going through O and D. Third, when more than one path leads from an intersection D, q is the probability that one link is chosen, and p is the probability that the other intersection is chosen next. Consequently, the probabilities of p and q equal unity ($p + q = 1$). The choice at any intersection is equiprobable ($p = q = \frac{1}{2}$). This assumption is a consequence of two alternatives. Either the aggregate path selection is not influenced by environment quality and the environment is assumed to be qualitatively uniform: or aggregate path selection is not influenced by environmental quality, and the environment is not qualitatively uniform. Finally, whenever the third assumption contradicts the second, the third is overruled. In other words, once a person has arrived at a grid boundary going through D, he will continue his path along this boundary until he reaches D (q = 1, p = 0; q = 0, p = 1, respectively).

Taking these assumptions as stated and using the binomial theory, Garbrecht constructs two models to describe the ways pedestrians can walk from O to D:

(1) all paths from O to D are equally likely; this behavior is termed <u>random paths</u>.

(2) choice at street intersection is equiprobable; this model is called <u>random walk</u>.

Before exploring the random walk and random path models, Garbrecht calculates the number of different paths which can lead to any particular intersection in the rectangular grid. For example, at an intersection B3, there are three possible paths: (1) A1-A2-A3-B3; (2) A1-B1-B2-B3; and (3) A1-A2-B2-B3. At intersection D2 there are four discrete paths: (1) A1-B1-C2-D1-D2; (2) A1-B1-B2-C2-D2; (3) A1-A2-B2-C2-D2; and (4) A1-B1-C1-C2-D2. These examples demonstrate that for any intersection within the grid, the number of different paths can be calculated by adding the number of paths for the adjacent intersections. Therefore, for intersection C3 the number of discrete paths can be determined by adding the path calculations for B3 and C2 which are the adjacent intersections. Since there are three discrete paths to B3 and three different paths to C2, six discrete paths terminate at C3.

Utilizing the above procedure of calculating the number of paths which can pass through an intersection, Garbrecht constructs the model which he terms random paths. The assumption underlying this model is that each path in the rectangular grid is equally likely. From the origin to the destination there are six different paths: (1) A1-B1-C1-C2-C3; (2) A1-B1-B2-C2-C3; (3) A1-B1-B2-B3-C3; (4) A1-A2-A3-B3-C3; (5) A1-A2-B2-B3-C3; (6) A1-A2-B2-C2-C3. Each of these six paths has 1/6 as the probability of occurrence. Figure 2c gives the corresponding transitional probabilities for each link, and the probability that a path starting at the origin reaches a particular intersection. These probabilities are calculated as follows: Take the intersection A2. From an analysis of the six paths starting at the origin, three lead to A2. The other three lead to B1. Therefore, half of the paths leaving the origin reach each intersection. In other words, if a path starts at the origin, the probability that it will reach A2 is ½; and this is the transitional probability between the two intersections. Now take the intersection A3. One of the six discrete paths leads to A3 (A1-A2-A3-B3-C3). Consequently, the probability that a trip starting at O reaches this intersection is 1/6. Three of the six paths reach A2, but of these three paths only one will continue to A3. This means that the transitional probability between A2 and A3 is 1/3 while the transitional probability A2 and B2 is 2/3. Finally, take intersection B2. Four of the paths leaving the origin pass through intersection B2. Of these four paths, two continue to B3 on the next stepwise move (e.g., A1-B1-B2-B3-C3 and A1-A2-B2-B3-C3) and two paths move to C2 (e.g., A1-A2-B2-C2-C3 and A1-B1-B2-C2-C3). Therefore, the transitional probabilities are as follows: B2 to B3 is equal to ½ and B2 to C2 is equal to ½. In a similar manner, the transitional probabilities can be calculated for all intersections.

Garbrecht's second model, termed random walk is based on the assumption of equiprobable choice at each intersection. This means that all transitional probabilities between intersections are ½ while transitional probabilities between boundary links are 1. Though we still have the same number of discrete paths through the grid, the probabilities of different paths are no longer equally likely. Four paths have a probability of 1/8. These paths are the following: (1) A1-B1-B2-C2-C3; (2) A1-B1-B2-B3-C3; (3) A1-A2-B2-B3-C3; and (4) A1-A2-B2-C2-C3. Since the likelihood of a trip is measured by multiplying the transitional probabilities of all links which compose a trip, these four paths pass through three intersections within the grid (transitional probability equals ½) and one boundary intersection (transitional probability equals 1). Therefore, the calculated probability for each of these four paths equals 1/8 (½ x ½ x ½ x 1 = 1/8). The other two paths in this model have a probability occurrence of ¼. These paths consist of two intersections within the grid and two boundary links (e.g., A1-B1-C1-C2-C3 and A1-A2-A3-B3-C3). Consequently, if transitional probabilities are ½ through the grid (except on the boundaries) the different trips are not equally likely. Equiprobable choices at intersections does not imply equiprobable trips.

Markov Model of Pedestrian Movement.

Garbrecht's (1973) second theoretical approach to the study of pedestrian movement involves the utilization of Markov chain analysis. Garbrecht believed that the random walk model (equiprobable choice at each intersection) and the random path model (complete paths from an origin to a destination are equally likely) were both inflexible and not likely to be supported by empirical findings. In fact, in the one empirical study completed by Garbrecht (1971), an analysis of 71 pedestrian paths through an oblong parking lot suggested that actual rules describing aggregate pedestrian behavior are not adequately represented by either of the two models. In this study it was found: (1) for trips that are along a boundary the probability of a change of direction may be considerably smaller than for paths that have left a boundary and are inside a grid; (2) for intersections near and on the line connecting origin and destination, there may be a tendency to stay on that side of the diagonal on which the trip was started or, in the case of crossing, to stay close to the diagonal.

In studying a grid utilizing a Markov chain analysis, we are dealing with time periods and path states. In studying a walk, we assume that time-distance is proportional to length of path and time-distance is minimized; that is, we exclude from the analysis all paths that imply detours. We also assume that all paths are moving from south-west to north-east. All states of the Markov process which can be reached after n steps, that is, all states which a walk may be in at t + n are those connected by diagonal straight lines. For the grid the time periods and states are as follows:

t	0
t + 1	States 13, 14
t + 2	States 9, 10, 11, 12
t + 3	States 1, 5, 6, 7, 8
t + 4	States 1, 3, 4, 2
t + 5	States 1, 2
t + 6	0

At time t (for an equiprobable choice) the probability on entering states 13 or 14 is .5. At state t + 1 the initial path positions are now State 13 and 14. The next time period is t + 2 where the path must move to States 9, 10, 11, or 12 (all states on the diagonal t + 2). State 13 can only proceed to States 11 or 12, while State 14 can only proceed to States 11 or 12 at t + 2. At time t + 3 State 9 must proceed to State 1 (probability equals 1). State 10 must proceed to States 5 or 6. Likewise State 11 must go to states 5 or 6. State 12 must proceed to States 7 or 8. At time t + 3 there are the following five states: States 1, 5, 6, 7, and 8. States 1 and 5 must proceed to State 1 (probability equals 1). State 6 must go to States 3 or 4. State 7 must proceed to States 3 or 4. State 8 must go to State 2 (probability equals 1). At time t + 4 there are the following four states: States 1, 3, 4, and 2. States 1 and 3 must go to State 1 (probability equals 1). States 4 and 2 must go to State 2 (probability equals 1). At t + 5 the states are 1 and 2. Both States 1 and 2 are final states with probability equal to 1. This is the complete transition matrix probabilities for a 3 x 2 grid.

It should be noted that the structure of a particular matrix is to a certain extent arbitrary. It depends to some degree on the way one numbers the states and the way one arranges them in the matrix. The manner of defining states can also lead to constraints on the behavior that is possible and the corresponding probabilities. For example, in time steps t + 1 and t + 2, the assumptions of the Markov model imply that the probability of continuing straight ahead from State 14 to State 12 is the same as moving from State 14 to State 11. Furthermore, the assumptions of the model imply that the choice of paths between t + 1 and t + 2 is independent of the choices of path states between t and t + 1 and the choices of state between t + 2 and t + 3. If this were not so (e.g., independence assumption violated), one could argue that at a particular point in time, say t + 1, the transition to the next time period (t + 2) would depend significantly on past path states. This would violate the assumptions underlying the Markov Model.

The concept of transition matrixes can now be applied to the equiprobable choice and the equiprobable path models. Since the calculations of the transition matrixes is the centerpiece of the Markov Model, we will examine the calculations of the conditional and cumulative probabilities in detail.

In the equiprobable choice model the probability of moving from any state is .5. The first move in the Markov chain is from t to t + 1. At the origin at time t, the path can move either to State 13 or State 14 with conditional probabilities of .5. The cumulative probabilities for both states are also .5.

The next time move in the model is from t + 1 to t + 2. The conditional probabilities are as follows: p(State 9/State 13 = .5), p(State 10/State 13 = .5), p(State 11/State 14 = .5), and p(State 12/State 14 = .5). All other conditional probabilities are equal to zero since they are not logically possible in the model as constructed.

For time t + 1 to t + 2 there are six cumulative probabilities for each of the six independent states. Since States 13 and 14 are the only possible states through which the path can proceed from the origin, their cumulative probabilities equal .5 (p(13) = .5 and p(14) = .5). The cumulative probability of State 9 is calculated by determining the probability of the path 13-14 (States 13-14). This calculation is determined by multiplying their probabilities (e.g., p(13) = .5, p(14) = .5, p(13-14) = (.5)(.5) = .25; therefore the p(9) = .25). The cumulative probability of State 10 is calculated by determining the path 13-10 (e.g., p(13) = .5, p(10) = .5, p(13-10) = (.5)(.5) = .25; therefore p(10) = .25). For the cumulative probability of State 11, the probability of path 14-11 is .25 (p(14) = .5, p(11) = .5, p(14-11) = (.5)(.5) = .25; therefore p(11) = .25). Similarly, the cumulative probability of State 12 equals .25 (p(14) = .5, p(12) = .5, p(14-12) = (.5)(.5) = .25; therefore p(12) = .25).

The next time move is from t + 2 to t + 3. The conditional probabilities are as follows:

p(State 9/State 1) = 1 (State 1 is an absorbing boundary which is in steady state.)

p(State 10/State 5) = .5   State 10/State 6) = .5
p(State 11/State 5) = .5   State 11/State 6) = .5
p(State 12/State 7) = .5   State 12/State 8) = .5

All other conditional probabilities are equal to zero because they are not logically or structurally possible given the dimensions of the grid.

For the calculation of the cumulative probabilities in t + 3, the states are 1, 5, 6, 7, and 8. Again, a cumulative probability is the probability that a path starting at the origin will lead to a particular state. For State 1 there is only one possible path: Path 13-9-1. The probability of this path and consequently State 1 is .25 (p(13) = .5, p(9) = .5, p(1) = 1, p(13-9-1) = (.5)(.5)(1) = .25). For State 5, there are two possible paths: Path 13-10-5 and Path 14-11-5. To determine the cumulative probability of State 5 the probabilities of these two paths are added together: p(Path 13-10-5) = (.5)(.5)(.5) = .125; p(Path 14-11-5) = (.5)(.5)(.5) = .125; p(13-10-5) + p(14-11-5) = .125 + .125 = .25). Therefore, the probability of State 5 = .25. For State 6 there are two possible paths: Path 13-10-6 and Path 14-11-6. The cumulative probability of State 6 is .25: p(13-10-6) = (.5)(.5)(.5) = .125, p(14-11-6) = (.5)(.5)(.5) = .125; p(13-10-6) + p(14-11-6) = .125 + .125 = .250. For State 7 there is one path: Path 14-12-7. The cumulative probability for State 7 is .125: p(14-12-7) = (.5)(.5)(.5) = .125. Likewise, for State 8 there is only one possible path: 14-12-8. The cumulative probability is .125: p(Path 14-12-8) = (.5)(.5)(.5) = .125.

The next time move is from t + 3 to t + 4. The conditional probabilities are as follows: p(state 3/state 6) = .5, p(state 4/state 6) = .5, p(state 3/state 7) = .5, and p(state 4/state 7) = .5.

For the calculation of the cumulative probabilities in t + 4, the states are 1, 3, 4, and 2. For State 1 there are three possible paths: Path 13-9-1-1, Path 14-11-5-1, and Path 13-10-5-1. To determine the cumulative probabilities of State 1 the probabilities of the three paths are added together. For State 1 the cumulative probability is .5:

p(path 13-9-1-1) = (.5)(.5)(1)(1) = .25

p(path 14-11-5-1) = (.5)(.5)(.5)(1) = .125

p(path 13-10-5-1) = (.5)(.5)(.5)(1) = .125

p(state 1) = .25 + .125 + .125 = .50

For State 3 there are three different paths: Path 13-10-6-3, Path 14-11-6-3, and Path 14-12-7-3. To determine the cumulative probability of State 3 the probabilities of the three paths are added together. For State 3 the cumulative probability is .19:

p(path 13-10-6-3) = (.5)(.5)(.5)(.5) = .063

p(path 14-11-6-3) = (.5)(.5)(.5)(.5) = .063

p(path 14-12-7-3) = (.5)(.5)(.5)(.5) = .063

p(state 3) = .063 + .063 + .063 = .19

For State 4 there are three different paths: Paths 14-11-6-4, Path 14-12-7-4, and Path 13-10-6-4. For State 4 the cumulative probability is .19:

p(path 14-11-6-4) = (.5)(.5)(.5)(.5) = .063
p(path 14-12-7-4) = (.5)(.5)(.5)(.5) = .063
p(path 13-10-6-4) = (.5)(.5)(.5)(.5) = 063
p(state 4) = .063 + .063 + .063 = .19

For State 2 there is only one possible path: Path 14-12-8-2. The cumulative probability is .125: p(path 14-12-8-2) = (.5)(.5)(.5)(1) = .125.

The next time period is t + 5. The conditional probabilities are as follows: p(state 1/state 1) = 1, p(state 1/state 3) = 1, p(state 2/state 4) = 1, and p(state 2/state 2) = 1.

For the calculation of the cumulative probabilities at t + 5, the states are state 1 and state 2. For state 1 at t + 5 there are the following six different paths: Path 13-9-1-1-1, path 13-10-5-1-1, path 13-10-6-3-1, path 14-11-5-1-1, path 14-12-7-3-1, and path 14-11-6-3-1. The determination of the cumulative probability of State 1 at t + 5 is calculated by adding the probabilities of the six paths together. For state 1 the cumulative probability is .69:

p(path 13-9-1-1-1) = (.5)(.5)(1)(1)(1) = .25
p(path 13-10-5-1-1) = (.5)(.5)(5)(1)(1) = .125
p(path 13-10-6-3-1) = (.5)(.5)(.5)(.5)(1) = .063

p(path 14-11-5-1-1) = (.5)(.5)(.5)(1)(1) = .125

p(path 14-12-7-3-1) = (.5)(.5)(.5)(.5)(1) = .063

p(path 14-11-6-3-1) = (.5)(.5)(.5)(.5)(1) = .063

p(state 1) = 25 + .125 + .063 + .125 + .063 + .063 = .069

The determination of the cumulative probability of State 2 at t + 5 is calculated by the addition of the probabilities of the following four paths: path 14-12-8-2-2, path 14-11-6-4-2, path 14-12-7-4-2, and path 13-10-6-4-2. For state 2 the cumulative probability is .32:

p(path 14-12-8-2-2) = (.5)(.5)(.5)(1)(1) = .125

p(path 14-11-6-4-2) = (.5)(.5)(.5)(.5)(1) = .063

p(path 14-12-7-4-2) = (5)(.5)(.5)(.5)(1) = .063

p(path 13-10-6-4-2) = (.5)(.5)(.5)(.5)(1) = .063

p(state 2) = .125 + .063 + .063 + .063 = .32

This analysis gives the Markov transitional and cumulative probabilities for the equiprobable path model. Its value is that it gives a theoretical model of pedestrian movement for a 2 X 3 grid which can be compared to actual pedestrian data. Garbrecht's own attempts at comparing actual pedestrian data with the Markov model has been limited and inconclusive. Nonetheless, Garbrecht's model and methodology has many advantages when compared with transitional methods.

First, route selecting behavior of pedestrians can be described and analyzed by utilizing frequency data on path choice for different experimental conditions, such as street networks of various block size and grid length, different purposes of walking, and for uniform as well as nonuniform environments.' The analysis of these types of data will lead to different types of matrixes governing transitional probabilities. Secondly, these transitional matrixes can be utilized for the specification of conditions: (a) to estimate distributions for new environments; (b) to design street environments that lead to certain desired distributions and avoid undesired ones; (c) to predict the impact of changes in existing environments; and (d) to estimate frequencies in particular intersections and links. Thirdly, the analysis focuses on individual trips and thereby has a longitudinal component that supplements cross-sectional frequency counts. In the usual pedestrian study the cross-sectional approach is employed because the level of analysis is static. An appropriate analogy is that the cross-sectional approach is similar to examining a still picture of a particular setting while the transitional matrix approach is like an examination of a movie of the same setting. The Markov approach is a much closer approximation to the reality since pedestrian behavior is one in motion.

Another advantage of this method is that path selection can be investigated. Although pedestrian research has provided information on velocity, density of pedestrian flow, and acceptable interpersonal distances, little is known about the manner in which people select paths through uniform environments, nor about the influence that structuring the environment has on route selection. Also, little is known how climatic variables influence pedestrian movement. By being able to estimate the influence environmental parameters have on behavior, one can predict path selection under different conditions and circumstances. Thus it would be possible to assess at a macro-level the influence of such variables as climatic conditions, different street widths, pedestrian crowding, and various types of street designs.

Finally, the use of transitional probabilities allows one to predict frequencies for any particular intersection in a grid without bothering about the number of people that walk through the other links. To estimate this number it will be sufficient to know how many subjects walk from an origin to the corresponding destination. For example, assume fifty people enter from the origin and that one would like to know how many people will walk from intersection (2,2) to (3,2). One could estimate the frequency as follows: people may walk through state 4 from state 6 or state 2. The corresponding cumulative probability is .19. Therefore we have 50 X .19 = 10 as the estimated number of people that will walk through state 4, that is from (2,2) to (3,2).

Behavioral Maps.

In examining pedestrian movement and behavior as it covaries with wind gustiness, the method of behavioral maps will also be employed. This method of investigating behavior in environmental settings has been most fully developed by Ittelson, Rivlin, and Proshansky (1970). They begin with the premise that behavior always occurs within the limits of physical surroundings. This premise which seems obvious has not usually been recognized by traditional psychology. For the psychologist, behavior is a phenomenon investigated in a neutral experimental setting. Usually it has not been recognized that the environment itself profoundly affects the behavior which is to be analyzed. In opposition to this traditional view, environmental psychology has recognized the importance of relating various aspects of behavior to the physical settings in which it occurs. These studies have usually employed a methodology called behavioral mapping. The distinguishing feature of any behavioral map is the description of behavior as it relates to the physical setting. Consequently, in general this technique is a macro methodology for studying influences on behavior in the field.

The basic prototype for the behavioral map is the architect's floor plan. The basic map is a scale drawing of the physical space with all the salient physical features. In this dissertation the method has been extended in that three dimensional maps and grids have been constructed for each site under investigation. The primary purpose of the grid is to relate behavior to its physical locus. An index mark or other notation at the intersection of a row and a column indicates whether the behavior occurred at that specific location. This method allows one to construct a profile of the behavioral/environmental relationship. Other possible ways of presentation include graphs, pictures, and tables. Again, these modes may be superimposed on the basic map. The basic form of the map is tabular with the rows and columns sequentially marked.

Proshansky has pointed out that the information needed to construct a behavioral map as a methodological tool differs in two ways from the prototypical architect's floor plan. First in the nature of the behavioral category. In most research the behavioral categories must be operationalized (i.e., categories which are explicit and precise). Further, the categories must be relevant to the particular research under consideration. For example, in this dissertation the categorization of <u>relevant</u> categories which could be operationalized proved to be a major difficulty. Although spatial location in the grid was relatively easy to accomplish, the analysis of complicated behavior proved to be very difficult to investigate. Hence, the level of behavioral analysis in the map had to be limited to a macro analysis. The second characteristic of behavioral maps which differentiate them is that they are constructed empirically. Behavioral maps always describe observed behavior. In addition the description of observed behavior must be quantitative. In almost all cases quantitative measures of behavior are one of the primary characteristics of the map. In general these two characteristics of behavioral maps--the analysis of behavior into relevant categories and the empirical observation of these behavioral categories--will also constitute the two major technical difficulties of behavioral maps.

CHAPTER III

METHODS

General Design.

The environmental effects of wind/building interactions on pedestrian behavior and pedestrian flow patterns in a complex urban setting can be investigated directly by employing specific urban settings as their own controls and studying various conditions in them. The general design of this analysis is based on the fact that specific settings must be studied under natural conditions rather than in the laboratory. Although wind-tunnel investigations of human behavior can provide useful guidelines for determining critical limits of ground-level wind speeds, this approach cannot capture the holistic sense of the overall structures of pedestrian movement in a real-world setting (Hutt & Hutt, 1970). In order to make an objective evaluation of certain aspects of pedestrian behavior as it covaries with changing wind conditions, this study employed two complementary approaches. One involved the acquisition of on-site data, including the detailed physical description of pedestrian-level winds coupled with time-lapse movie recordings of pedestrian movement in the wind field at the test locations. The second approach involved the use of a questionnaire distributed to people working in two of the office buildings adjacent to two of the test locations. In addition, economic data were obtained from several shops and restaurants in the vicinity of one of the test locations.

Test Sites.

Prior to the actual collection of data, a number of test locations and vantage points in the downtown of Boston were screened. Four sites were selected that provided a range of different public places and prevailing wind conditions. These were:

Site A (1) the sidewalk area adjacent to a 500-foot (152-meter) building where it is generally recognized that unpleasant wind conditions are frequently encountered (Fig. 1);

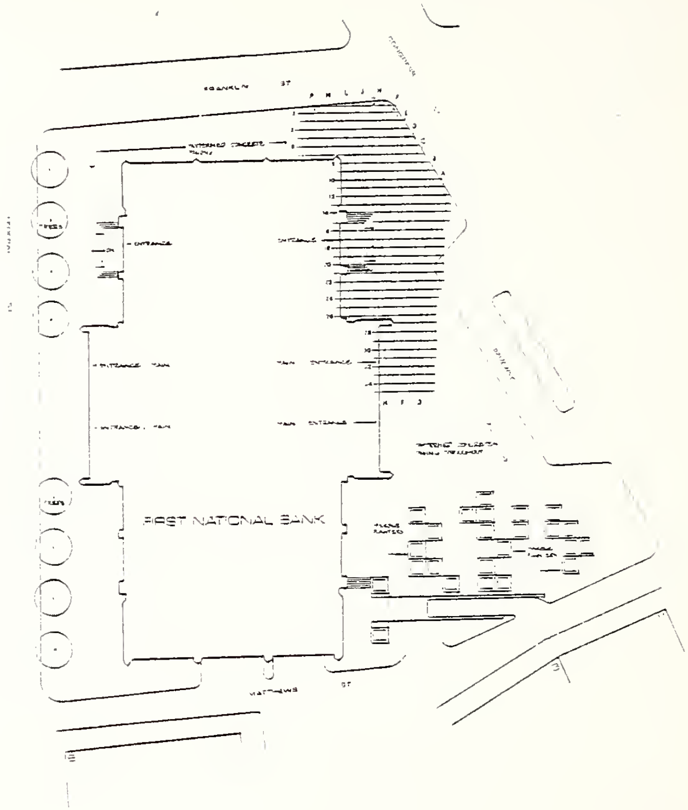
Site B (2) the entrance walkway to a 600-foot (183-meter) building where fast wind conditions are known to occasionally occur (Fig. 2);

Site C (3) the public plaza adjoining Boston City Hall (Fig. 3);

Site D (4) a sitting and strolling area on the edge of the Boston Commons, a large public park (Fig. 4).

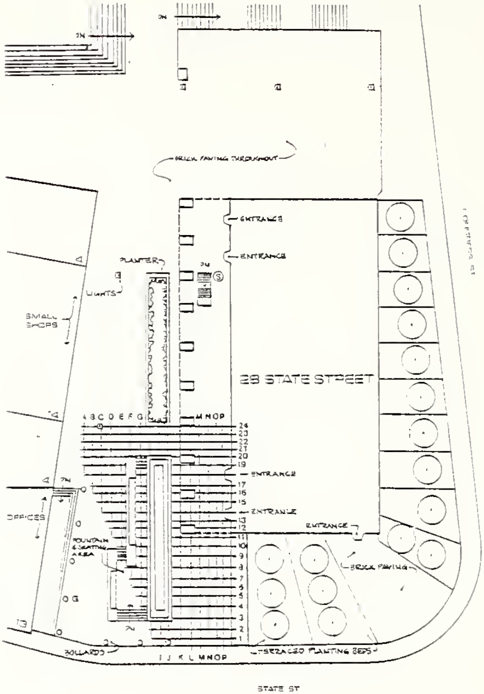
All sites were suitable for location of wind-measuring instrumentation without disrupting traffic in the vicinity.

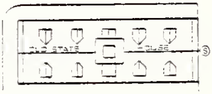
Fig. 1. Study Site A



STUDY SITE A
500' HIGH RISE TOWER

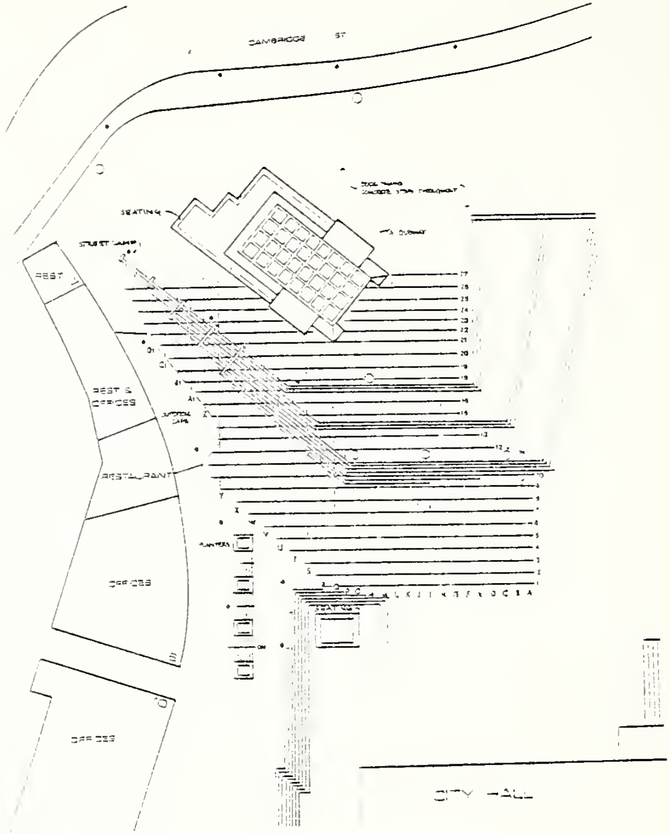
Fig. 2. Study Site B





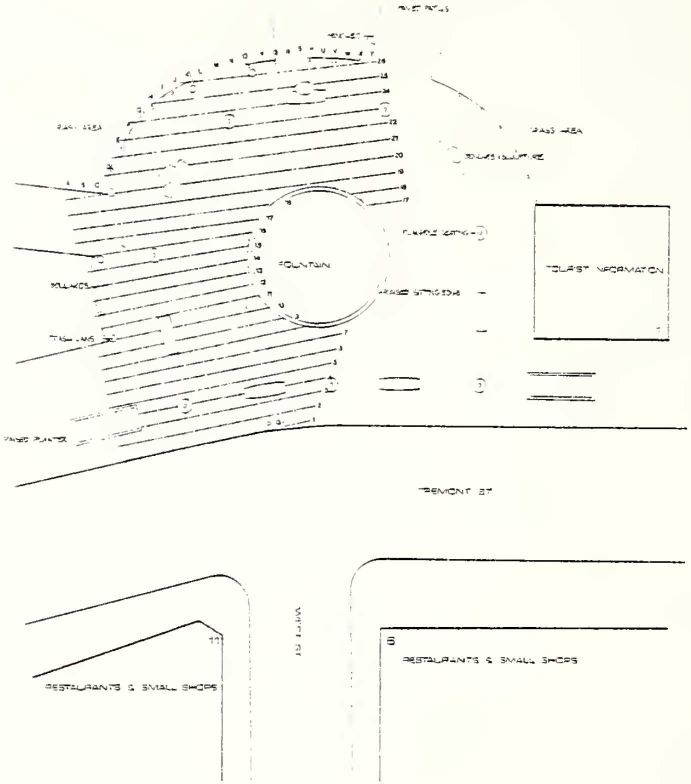
STUDY SITE B
600' HIGH RISE TOWER

Fig. 3. Study Site C

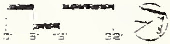


STUDY SITE C
LARGE URBAN PLAZA

Fig. 4. Study Site D



STUDY SITE D
URBAN PUBLIC PARK



Test Sessions.

Wind-speed and observational data were collected at all sites for three different seasons: winter (December 21-March 21), spring (March 21-June 21), and summer (June 21-September 21). For each season data was collected for at least two days: (1) a baseline day on which the ambient wind speed measured at Logan Airport by the Weather Service was less than or equal to 10 mph (4.5 m/sec); and (2) a test day, in which the ambient wind speed measured at Logan was greater than or equal to 20 mph (9.1 m/sec).

Data were collected at the test sites in the same sequence on each observation day: Site A--9:00 A.M.; Site B--10:00 A.M.; Site C--11:30 A.M.; and Site D--2:00 P.M. A 20-minute period of actual data was recorded at each observation site.

Behavioral and Path Analysis.

For the purposes of making an evaluation of certain aspects of behavior and pedestrian flow in relationship to changing wind speeds, an unobtrusive observational technique, time-lapse photography, was employed at each of the study sites. One of the primary advantages of this procedure was that the experimenter's interference with behavior and movement in the setting was minimized. This was particularly crucial with subjects in open and public places, where the range of gathering data was limited (Webb & Campbell, 1966). Moreover, time-lapse filming enabled behavioral data and pedestrian flows to be recorded simultaneously with the on-site wind measurements. This allowed for the analysis of observed activities both spatially and temporally as these variables covaried with wind speed and direction. As this method is not concerned with controlled laboratory manipulation of variables, quantification and analysis of variables is more difficult to achieve. However, the aforementioned benefits make this procedure essential to the studying human behavior in real-settings. For each of the sites a designated viewing area was chosen from still photographs. Physical features of each area recorded in the stills were used as reference points in setting up the movie camera at each session.

A Cannon Model 814 Auto Zoom super-eight movie camera with an interval timer and a standard heavy-duty tripod were used to record pedestrian movement. Recordings were made with Katachrome 40, type A color film, over each of the 20-minute observation periods at the rate of 1.4 frames/second and were coordinated with the wind-data acquisition through the use of hand signals and short-range portable radios.

Reduction of Recorded Data: Measurements.

The technique for recording pedestrian behaviors and paths from time-lapse photography was developed for this project because it allowed for data reduction and multiple reviewings of the films. Unlike observation, data which had been reduced from time-lapse films could be easily checked for reliability, and many characteristics of the data could be analyzed in coordination with on-site wind measurements. For the reduction of the films for purposes of analysis, a complex of standardized procedures were developed. In a typical reduction session, one person would operate the replay equipment and another would record behavioral data or path coordinates. The replay equipment consisted of a Kodak Ektagraphic MFS-8 movie projector with a special provision to advance films frame by frame.

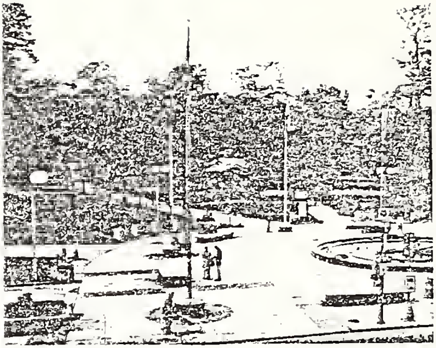
Prior to data analysis, two-dimensional perspective grid maps were created for each site. These perspective maps were constructed by projecting the film image of each site on tracing paper. The particular unique characteristics of the geographical and architectural aspects of each site were drawn on specific tracts. The actual grid lines and coordinates were drawn to scale from measurements taken directly at each site. For the grid maps of the office buidling and City Hall Plaza, each grid box represents an area of 25 square feet, 5 feet by 5 feet (2.3 square meters, 1.52 m by 1.52 m). Finally, the film itself is directly coded sequentially by marking every tenth frame beginning with frame 10 and terminating at frame 1600. This procedure provided a basis for the analysis of pedestrian movement and speed (i.e., one minute equals 82 frames). For each film analysis the corresponding perspective grid was superimposed on the appropriate projected film with the grid and film image coordinated by matching geographical and building reference points.

Collection of Path Data.

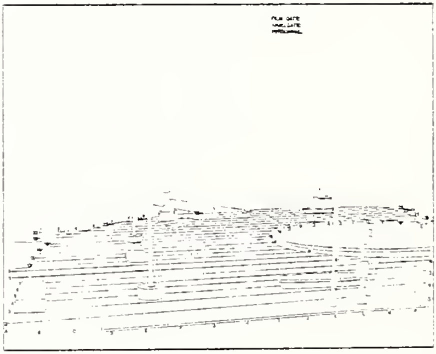
Individual pedestrian paths were analyzed by a standardized sequential frame-by-frame trace of a subject traversing the perspective grid map (see Figs. 5 - 7). The analysis of a subject was initiated when he made his initial step into the grid map. At this juncture the frame number was recorded and the map coordinates of the subject's lead foot were recorded. The film was then advanced one frame and the map coordinates were again recorded on a data sheet as well as the grid map itself. This procedure of sequential advancement of the film and the recording of the corresponding map coordinates was continued until the subject exited the grid. At that point the frame number was recorded as well as the final grid coordinates. Thus for each subject a set of sequential map coordinates representing his actual path was recorded in addition to a temporal log derived from the entrance and exit frame numbers. For the office building forty subjects for each observation were tabulated employing

Fig. 5. Photograph of Site D

Fig. 6. Perspective Grid of Site D



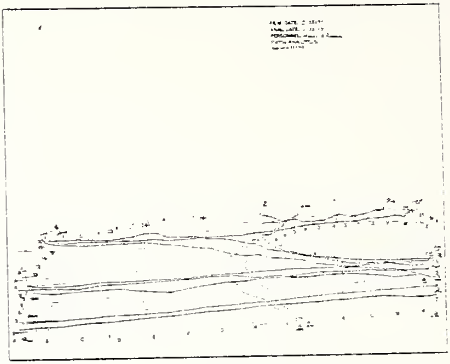
Photograph of site D illustrates the exact film image captured by the time-lapse movie camera.



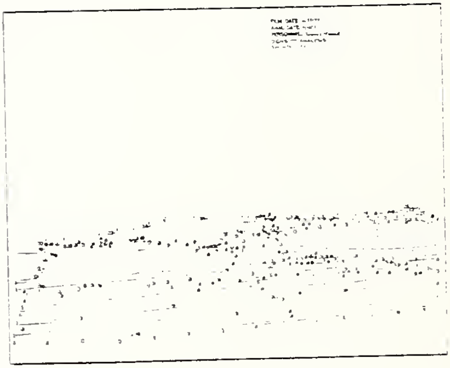
The perspective grid drawing onto which the film data gathered at site D were projected for analysis.

Fig. 7. Perspective Grid Showing Tracings of Pedestrian Paths

Fig. 8. Perspective Grid Showing a Pedestrian Density Pattern



The perspective grid [illegible] frame analysis [illegible]



The perspective grid [illegible] of film data this procedure. These subjects were distributed temporally throughout the film by following the paths of the first five subjects who entered the grid every two hundred frames. Hence the film was divided into eight equal fragments. As the City Hall Plaza is substantially larger than the other test sites, nine subjects were followed for each two hundred frames (i.e., seventy-two subjects) in the same manner. For each subject the sequential map coordinates were transferred to IBM cards for statistical analysis.

Density Analysis.

For each film the density was computed by sampling the film every thirtieth frame (i.e., 22 seconds) for forty consecutive samples (see Fig. 8). At each film sample the map coordinates for each subject were recorded. This procedure allowed for the construction of a spatial frequency map of each site as well as the calculation of the average density of the entire 20-minute test period.

Pedestrian Velocity.

For each subject the pedestrian velocity was calculated for twenty subjects for each session. The distance and temporal data were determined by calculating the number of grid squares a subject traversed and concurrently cataloguing the number of frames that corresponded to this path. This data was transformed into distance and time measurement by multiplying by the appropriate scale values.

Behaviors.

For each session various gross behaviors were calculated. During each session the number of individuals standing alone, standing in groups, and sitting were determined. In addition, for each of these gross behavioral categories, the average times were calculated throughout the session. Although the experimenters were interested in observing such behaviors as talking and eating lunch, this analysis was not possible because the resolution of the film would not allow for the observational determination of these behavioral categories. Consequently, the analysis was limited to gross motor behaviors.

Platoons.

For each session the number of individuals in various size groups were calculated for the entire session. Observation and calculation of the number of platoons of various sizes (two people through five people) were utilized as a gross measure of interpersonal distance among individuals during a session.

Sequential Path Analysis.

For each of the test sessions, the individual path data were analyzed and tabulated in a two-fold procedure. First, for each session the map coordinates for each subject were submitted to a conditional probability computer program that generates a probability matrix for each grid square in the perspective grid map (see Table 3). Except for boundary grid squares, each grid box is bounded by each adjacent squares. In the example below, grid box G2 is bounded by squares F1 to F3, H1 to H3, and G1 to G3.

F1 G1 H1

F2 G2 H2

F3 G3 H3

The computer program computes the conditional probabilities for Square G2; that is, by assuming that an individual is in Square G2, the program determines the probability that on the next step of the path the subject will be located in one of the adjacent grid squares. For that specific session, the program assembles a frequency count of the number of times all subjects in a session move from G2 to any of the adjacent squares. In addition, it also tabulates the number of occurrences that an individual remains in the same square for two consecutive times. These frequency counts are then utilized to generate the nine following conditional probabilities for our example: p(F1/G2), p(F2/G2), p(F3/G2), p(H1/G2), p(H2/G2), p(H3/G2), p(G1/G2), p(G2/G2), and p(G3/G2). Hence, a total of nine conditional probabilities are generated for

Table 3

Fortran Program for the Generation of Conditional Probabilities

```
      PROGRAM PROBS (INPUT=64,OUTPUT=64/136,TAPE1=64/80,
         TAPE2=64)

      INTEGER M1(60),M2(60),SQR(4000),OCR(806),FOL(806,9),
         DIM1,DIM2
      INTEGER LABEL(3)
      REAL     FREQ(806),PROB(806,9)
      COMMON   M1,M2,SQR,OCR,FOL,IFMT(5),JFMT(5),FREQ,PROB

      DATA  NUM,ERROR1,ERROR2,ERROR3,ERROR4,ERROR5,TOT
         /6*0,0./

      REWIND1    $   REWIND2

      PRINT 1000
 1000 FORMAT(1H1)
      DO 10 I=1,806
      OCR(I)=0
      DO 10 J=1,9
   10 FOL(I,J)=0

      READ (1,2222)LABEL
      WRITE(2,2222)LABEL
      PRINT   3333,LABEL
 2222 FORMAT(3A10)
 3333 FORMAT(1X,3A10,/,1H0)


      ****READ MAXIMUM DIMENSIONS.  MULTIPLY THEM TO FIND
                                 TOTAL NUMBER OF SQUARES****

      READ (1,2000)DIM1,DIM2
      WRITE(2,2000)DIM1,DIM2
 2000 FORMAT(R1,I2)
      L=DIM1*DIM2
      IF(L.GT.806)ERROR1=1

      ****READ THE NUMBER OF TRIPS TO BE PROCESSED****
      READ(1 *)NUMTRIP


      DO 30 I=1,NUMTRIP
      ****READ THE NUMBER OF DATA IN CURRENT TRIP****
```

Table 3 (continued)

Fortran Program for the Generation of
Conditional Probabilities

```
      READ(1,*)ND
      IF(ND.LE.59)GOTO 14
        PRINT*," TOO MANY DATA IN SERIES BELOW."
        ERROR2=1

      ****INC. NUMBER OF DATA BY ONE TO ALLOW FOR :01****
   14 NT=ND+1

      ****READ THE DATA FROM EACH INDIVIDUAL TRIP****
      READ(1,3000)(M1(J),M2(J),J=1,NT)
      PRINT  4000, (M1(J),M2(J),J=1,NT)
      IF(M1(NT).EQ.1R:.AND.M2(NT).EQ.1)GOTO 15
         PRINT*," :01 DOES NOT TERMINATE DATA SERIES ABOVE."
         ERROR3=1
 3000 FORMAT(20(R1,I2,1X)
 4000 FORMAT(20(2X,R1,I2)

      ****SUM DATA POINTS (W/O :01"S)****
   15 TOT=TOT+ND

      ****CONVERT 2 CO-ORD. LABELS TO SINGLE NUMERIC LABELS.
          ALSO SUM ALL DATA POINTS (INC. :01"S), AND IF :01
          IS ENCOUNTERED (:01=0), READ NEXT TRIP****

      DO 30 J=1,NT
      NUM=NUM+1
      IF(NUM.GT.4000)ERROR4=1
      M=(M2(J)-1)*DIM1+M1(J)
      SQR(NUM)=M

      IF(M.EQ.0)GOTO 30

      ****INDICATE IF A SQUARE IS NOT ADJACENT TO IT'S
          PREDECESSOR.****

      IF(J.EQ.1)GO TO 20
        IF(IABS(M1(J)-M1(J-1).LE.1.AND.IABS(M2(J)-M2(J-1).
           LE.1)GOTO 20
          ERROR5=1
          PRINT 5000,J
 5000 FORMAT(10H DATUM NO.,13,35H IS NOT ADJACENT TO
         PREVIOUS DATUM.)
```

Table 3 (continued)
Fortran Program for the Generation of Conditional Probabilities

```
  ****INC. NUMBER OF OCCURRENCES OF THE SQUARE****
20 OCR(M)=OCR(M)+1
30 CONTINUE


  ****IF ERROR IS DETECTED, STOP. ****
  IF(ERROR1.NE.0)STOP "GRID TOO LARGE (806 SQR MAX)"
  IF(ERROR2.NE.0)STOP "TOO MANY DATA/SERIES (59 MAX)"
  IF(ERROR4.NE.0)STOP "TOO MANY TOTAL DATA (4000 MAX)"
  IF(ERROR3.NE.0)STOP "MISSING TERMINATOR (:01)"
  IF(ERROR5.NE.0)STOP "NON-ADJACENT DATA"

  ****THIS LOOP GOES THROUGH THE SEQUENCE OF DATA,
      ASSIGNING ADJACENT SQUARES TO A 9 ELEMENT MATRIX
      AND INCREMENTING THE VALUE OF A SQUARE EVERY TIME
      IT FOLLOWS SQUARE(I-1)****

  DO 40 I=2,NUM

  IF(SQR(I-1).EQ.0.OR.SQR(I).EQ.0)GOTO 40

  J=SQR(I-1)
  N=(SQR(I)-J
  K=N+5
  IF(N.GT. 1)K=N-DIM1+8
  IF(N.LT.-1)K=N+DIM1+2

  FOL(J,K)=FOL(J,K)+1
40 CONTINUE


  ****DETERMINE FREQ"S OF INDIVIDUAL SQUARES AND COND.
      PROBS.****

  DO 60 I=1,L
  FREQ(I)=OCR(I)/TOT

  DO 50 J=1,9
  X=OCR(I)
50 PROB(I,J)=FOL(I,J)/X

60 CONTINUE
```

Table 3 (continued)

Fortran Program for the Generation of
Conditional Probabilities

```
      ****THIS SECTION OUTPUTS FREQ'S AND OCCURRENCES
          ADJUSTING DIMENSIONS AND FIELD WIDTHS ACCORDING
          TO THE ORIGINAL DATA.****


      NN=5
      IF(DIM1.LE.22)NN=6
      MM=DIM1*NN
      LL=NN-3
      ENCODE(50,6000,IFMT)DIM1,LL,MM,DIM1,NN
      ENCODE(50,7000,JFMT)DIM1,LL,MM,DIM1,NN,LL
 6000 FORMAT(*(13H1OCCURRENCES:/1X*I2*(*I1*R1,2X)/1X*I3*(1H-)/
     1       (*I2*I*I1*))*)
 7000 FORMAT(*(13H1FREQUENCIES:/X*I2*(*I1*XR1,2X)/X*I3*(1H-)/
     1       (*I2*F*I1*.*I1*))*)
      PRINT IFMT,(J,J=1,DIM1),(OCR(I),I=1,L)
      PRINT JFMT,(J,J=1,DIM1),(FREQ(I),I=1,L)


      ****OUTPUT PROBS FOR WALK PROGRAM****
      DO 70 I=1,L
   70 WRITE(2,8000)(PROB(I,J),J=1,9)
 8000 FORMAT(9(F8.6,1X))



      ****IF SQUARE DOES NOT OCCUR, DON'T PRINT ITS COND
          PROB MATRIX. CONVERT SINGLE NUMERIC LABEL BACK
          TO 2 CO-ORD LABEL.****

      REWIND1
      do 80 I=1,L

      IF(OCR(I).EQ.0)GOTO 80

      IALF=MOD(I,DIM1)
      IF(IALF.EQ.0)IALF=DIM1
      INUM=1+(I-1)/DIM1

      WRITE(1,9000)IALF,INUM,(PROB(I,J=1,9)
 9000 FORMAT(16H COND PROBS FOR ,R1,I2,1H:/,3(5X,3F8.4,/))
   80 CONTINUE
```

Table 3 (continued)

Fortran Program for the Generation of Conditional Probabilities

```
     ****REFORMAT COND PROB'S OUTPUT****
     CALL PPRINT


     REWIND2
     END




     ****THIS ROUTINE REFORMATS THE CONDITIONAL PROBABILITIES
                              INTO 3 COLUMNS.****

     SUBROUTINE PPRINT

     INTEGER TEXT(1519,12)
     COMMON TEXT

     REWIND1

     DO 10 J=1,12
     DO 10 I=1,1519
  10 TEXT(I,J)=1H


     K=-4
  20 K=K+5
     L=K+4
     ****READ IN A COND PROB MATRIX IN EACH OF 3 COLUMNS****
     DO 30 I=K,L
     READ(1,1000)(TEXT(I,J),J=1,4)
     IF(EOF(1))60,30
  30 CONTINUE
     DO 40 I=K,L
     READ(1,1000)(TEXT(I,J),J=5,8)
     IF(EOF(1))60 40
```

Table 3 (continued)

Fortran Program for the Generation of Conditional Probabilities

```
  40 CONTINUE
     DO 50 I=K,L
     READ(1,1000)(TEXT(I,J),J=9,12)
     IF(EOF(1))60 50
  50 CONTINUE
     GOTO 20

  60 PRINT 2000
     DO 70 I=1,L
  70 PRINT 3000,(TEXT(I,J),J=1,12)

1000 FORMAT(4A10)
2000 FORMAT(1H1)
3000 FORMAT(12A10)


     RETURN
     END
```

each grid square. In a hypothetical case, conditional probabilities are listed below for G2:

F1	.0556	G1	.1111	H1	.0000
F2	.1667	G2	.5000	H2	.1667
F3	.0000	G3	.0000	H3	.0000

For each square in the grid map, a similar conditional probability matrix is generated utilizing the identical procedure. Each session has its own series of conditional probability matrixes corresponding to that session's series of paths. For each session there are 612 such probability matrixes (except City Hall, which has 1024 matrixes). These were stored on magnetic tape for utilization in the second part of the analysis.

Step-Wise Sequential Path Model.

The final feature of the path analysis program allows one to generate a highest probability model path for any one of the test sessions employing the conditional probability matrixes for that session. In this mathematical procedure any grid square can be chosen as a starting point for the generation of a sequential highest probability path. Once the sequence begins, the walk program (see Table 4) will move sequentially to the adjacent grid square with the highest conditional probability. In the example below, when the path reaches square J3, the walk program retrieves the conditional probability matrix for

Table 4

Program Walk

```
      PROGRAM WALK(INPUT=64,OUTPUT=64,TAPE1=64,TAPE2=64)


      INTEGER     STEP(75),ALF(75),DIM1,DIM2,TOT,BACK,LABEL(3)
      DIMENSION   CONDPRB(806,9),PROB(806,9),NUM(75)
      COMMON      STEP,ALF,CONDPRB,PROB,NUM

      REWIND1   $   REWIND2

      PRINT 1000
 1000 FORMAT(1H1)


      READ(2,8000)LABEL
      PRINT  9000,LABEL
 8000 FORMAT(3A10)
 9000 FORMAT(1X,3A10,/,1H0)


      ****READ MAXIMUM DIMENSIONS****
      READ(2,2000)DIM1,DIM2
 2000 FORMAT(R1,I2)

      ****TOTAL NUMB. OF SQUARES = PRODUCT OF DIMENSIONS****
      TOT=DIM1*DIM2
      IF(TOT.GT.806)STOP "GRID SIZE TOO LARGE."

      ****READ IN COND PROBS****
      DO 10 I=1,TOT
      READ(2,3000)(CONDPRB(I,J),J=1,9)
 3000 FORMAT(9(F8.6,1X)
   10 CONTINUE


      ****READ A STARTING SQUARE AND THE BACKWARDS DIRECTION.
          CHANGE 2 CO-ORD LABEL TO SINGLE NUMERIC LABEL.****
   20 READ(1,4000)N1,N2,BACK
 4000 FORMAT(R1,I2,1X,R1)
      N=(N2-1)*DIM+N1
       ***STOP WHEN EOF OF TAPE1 ENCOUNTERED***
      IF(N2.EQ.50) GO TO 90
```

Table 4 (continued)

Program Walk

```
      ****IF INPUT WAS :01, STOP****
      IF(N.EQ.0)GOTO 90

      ****INPUT SQUARE BECOMES FIRST STEP****
      STEP(1)=N
      L=1


      ****RELOAD ORIG. COND. PROB. VALUES, BUT CHANGE ALL
          VALUES IN THE BACKWARD DIRECTION TO ZERO****
      CALL NOBACK(BACK,K1,K2,K3)

      DO 30 J=1,9
      IF(J.EQ.K1.OR.J.EQ.K2.OR.J.EQ.K3.OR.J.EQ.5)GOTO 25
        DO 24 I=1,TOT
  24    PROB(I,J)=CONDPRB(I,J)
        GOTO 30
  25      DO 29 I=1,TOT
  29      PROB(I,J)=0
  30  CONTINUE


      ****FIND MOST PROBABLE NEXT SQUARE****
  40  I=1
      X=PROB(N,1)
      FLAG1=0
      DO 50 J=2,9
        IF(PROB(N,J).EQ.X.AND.X.NE.0)FLAG1=1
          FLAG1=0
              I=J
              X=PROB(N,J)
  50  CONTINUE


      IF NON-ZERO EQUAL PROB'S ARE FOUND INDICATE SO.****

      IF(FLAG1.EQ.0)GOTO 51
        CALL CONVERT(N,I1,I2,DIM1)
        IF(FLAG1 NE.0)PRINT 5000,N,I1,I2
5000  FORMAT(28H EQUAL COND PROBS IN SQUARE ,13,2H (,R1,I2,2H),,
    1       15H FIRST ONE USED)
```

Table 4 (continued)

Program Walk

```
    ****IF NOT AT END OF TRIP,(DEFINED AS FINDING A SQUARE
        WHOSE COND PROBS ALL = 0 OR HAVING TAKEN 75 STEPS),
                                        CONTINUE WITH WALK.****
 51 IF(X.EQ.0.OR.L.EQ.75)GOTO 70

    ****ZERO OUT SQUARE SO THAT IF PROGRAM RETURNS TO IT,
        THE PATH WILL TERMINATE.****
    DO 60 J=1,9
 60 PROB(N,J)=0
    ***DO NOT HAVE TWO PATHS COINCIDE***
    CONDPRB(N,I)=0.0

    ****TRANSLATE POSITION IN 3 X 3 MATRIX TO ACTUAL SQUARE****
    K=N+I-5
    IF(I.LE.3)K=N-DIM1+I-2
    IF(I.GE.7)K=N+DIM1+1-8

    ****STORE MOST LIKELY SQUARE****
    L=L+1
    STEP(L)=K
    N=K



    ****TRANSLATE SINGLE LABEL BACK TO 2 CO-ORD LABEL****
 70 DO 80 I=1,L
 80 CALL CONVERT(STEP(I),ALF(I),NUM(I),DIM1)

    ****OUTPUT PATH****
    PRINT 6000,BACK,(ALF(I),NUM(I),I=1,L)
6000 FORMAT(*0MOST LIKELY SEQUENCE (BACKWARDS DIRECTION -
       *,R1,2H):,
   1        /2X,13(R1,I2,3X)/(3X,12(R1,I2,3X)))
    PRINT 7000
7000 FORMAT(1H-)

    ****RETURN FOR NEXT STARTING POINT****
    GOTO 20


 90 REWIND1   $   REWIND2
    END
```

Table 4 (continued)

Program Walk

```
  ****THIS ROUTINE DETERMINES WHICH 3 OF THE 9 COND.
      PROBS ARE IN THE BACKWARDS DIRECTION DENOTED BY
      THE PARAMETER 'I'.****

  SUBROUTINE NOBACK(I,K1,K2,K3)
  IF(I.EQ.1RT)GOTO 1
  IF(I.EQ 1RB)GOTO 2
  IF(I.EQ.1RL)GOTO 3
  IF(I.EQ.1RR)GOTO 4
  STOP "INCORRECT DIRECTION CODE"
1 K1=1   $   K2=2   $   K3=3   $   RETURN
2 K1=7   $   K2=8   $   K3=9   $   RETURN
3 K1=1   $   K2=4   $   K3=7   $   RETURN
4 K1=3   $   K2=6   $   K3=9   $   RETURN
  END



  SUBROUTINE CONVERT(N,I1,I2,IDIM)
  I1=MOD(N,IDIM)
  IF(I1.EQ.0)I1=IDIM
  I2=1+(N-1)/IDIM
  RETURN
  END
```

square J3 and moves to square J4, which has the highest conditional probability (*pJ4/J3 = .3333). Next, at square J4, the conditional probability matrix for square J4 is retrieved from computer memory and the walk program moves to square J4 (*pJ4/J4 = .6250).

Conditional Probability for J3:

J2	.1667	J2	.0000	K2	.0000
J3	.1667	J3	.1667	K3	.1667
J4	.0000	J4*	.3333	K4	.0000

Conditional Probability for J4:

J3	.0000	J3	.0000	K3	.0000
J4*	.6250	J4	.3750	K4	.0000
J5	.0000	J5	.0000	K5	.0000

This step-wise procedure progressively generates a highest probability path, terminating when it reaches a boundary endpoint.

This step-wise program follows several rules, which are not optional. Rule 1: the walk program will not remain in the same grid square for two consecutive sequential moves. Hence the conditional probability of the path remaining in the same square is ignored. This provision prevents a program loop. Rule 2: the walk program will not return to the previous square even if that square's probability is highest of any of the adjacent squares. Thus, in the previous example J4 could not return to J3 even if J3 were the highest probability square. This provision also prevents a loop of continuous exchange between the two squares. Rule 3: to maintain a forward direction to the path once it has been initiated, a sequential move cannot progress in the direction from which the path originated. Therefore, if a path begins from a north coordinate on the map, the path cannot move in a north direction. This provision prevents a path from moving backwards once it is initiated. This provision was built into the computer program in order that the paths move in a direction which is similar to aggregate pedestrian movement. Rule 4: if a map square has already been utilized by a higher probability path, a subsequent path cannot move to that square. This pertains only to paths that are conditionally related and moving in the same direction on the map. Instead, that path will move sequentially to the next highest probability square. Therefore, the paths are hierarchically ranked from one to seven. This provision creates a distance path for each sequential run.

Questionnaire and Economic Data.

Concurrently with the time-lapse films and wind measurements, a questionnaire was administered to individuals working in office buildings adjacent to sites A and C. This questionnaire was developed to test individual attitudes and perceptions to wind conditions on several behavioral scales. This instrument contained a technique developed by Hershberger (1974) that employs semantic differentials to test individual perceptions of photographs of our test sites. Also included was an attitude survey to evaluate individual opinions concerning the effects of wind conditions on their perceived behavior; and, finally, an assessment of whether behavioral responses to various wind conditions change or remain stable.

Prior to each test day, thirty copies of the questionnaire were distributed to a designated representative in each of the two office buildings. They were, in turn, asked to administer that group of questionnaires to office personnel during the course of that day. When completed, these were mailed to the Institute for Man and Environment for analysis.

As a supplement to observational data from the films and the questionnaire, shops and restaurants within the general study area were solicited for receipt information (i.e., number of register transactions per day). Several businesses provided daily receipt information, which in turn gave a detailed evaluation of the relationship between wind conditions and economic activity. All receipt days were compared to weather data from the National Weather Service's local climatological records as well as the actual on-site measurements.

CHAPTER IV

RESULTS

Films of pedestrian movement and behavior at each site were analyzed and evaluated separately. This procedure ensured that the specific characteristics of these diverse urban spaces could be evaluated relative to the particular wind configurations in each space. For each site the following analyses are examined: (1) the high-probability path analysis; (2) pedestrian velocity, density, and behavior; and (3) the pedestrian density distribution. Following these analyses is the questionnaire and economic data.

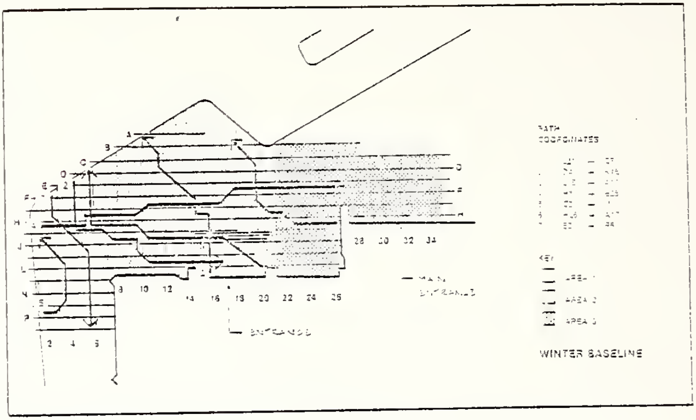
Site A--500-Foot Office Building.

Figure 9 displays the grid map for the 500-foot (152-meter) office building. The grid map has been divided into three areas for descriptive purposes. Area 1 defines a walkway bounded by the corner of the building and a major thoroughfare; area 2 designates the space adjacent to the entrance of the building; and area 3 represents the space adjacent to the lobby entrance of the office.

Figure 9 contains the plotted paths for the seven high-probability pedestrian paths for the winter baseline period. These paths were generated by the path analysis and walk programs. It will be noted that three of the high-

Fig. 9. Site A/Winter Baseline High Probability Paths

Fig. 10. Site A/Winter Test High Probability Paths


A
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22
24
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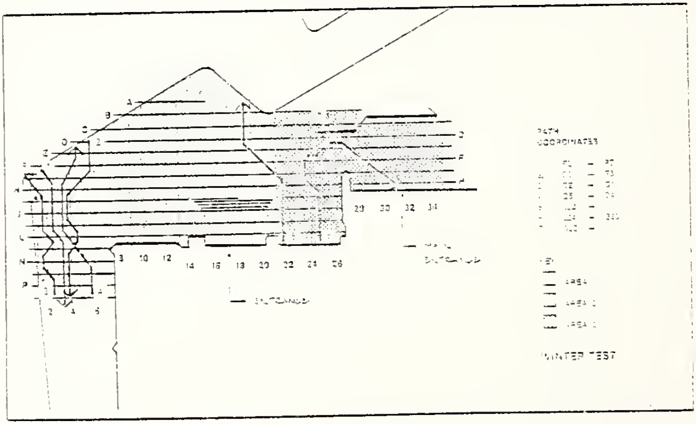
32
34
ENTRANCE
MAIN ENTRANCE
PATH COORDINATES
KEY
AREA 1
AREA 2
AREA 3
WINTER BASELINE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24
26
28
30
32
34
ENTRANCE
MAIN ENTRANCE
PATH COORDINATES
KEY
AREA
AREA 2
AREA 3
WINTER TEST

STUDY SITE
[illegible]

probability paths (1, 2, and 3) are either entrance or exit paths to the office building. Two paths (5 and 7) traverse area 1 and bypass the building. One path (4) traverses all these areas, exiting in area 3. Finally, one path (6) commences at the lobby and exits at area 2. The distinguishing characteristic of the distribution of these paths is that five of the seven paths traverse area 2 in some manner. Therefore, the space adjacent to the building entrance was utilized most frequently by pedestrians during this session.

Figure 10 shows the seven high-probability paths for the winter test period. It will be noted that four paths begin and terminate completely within area 1 (1, 2, 3, and 4), compared to the two paths in the baseline period. Two paths are completely encompassed by area 3 (6 and 7), and one path initiates in area 3 and terminates in area 2 (5). In contrast to the baseline session, wherein three paths either commence or exit at the entrance, no paths whatsoever traverse the building's entrance. Compared to the five paths that cross area 2 in the baseline period, only one path crosses area 2 in this session. Whereas in the baseline session five paths traverse at least two areas, in the test session six of the paths are entirely enclosed within area 1 or 3. Thus, compared to the baseline period, the distribution of high-probability paths in the test session exhibits a highly structured array of pedestrian paths.

Figure 11 contains the seven high-probability paths for the spring baseline period. Three paths either commence (paths 3 and 4) or terminate (6) at the building entrance. Although four paths begin in area 1, only one path (1) exits within this area. Finally, one path (7) begins in area 3 and exits in area 2. The distribution of paths is characterized by five paths traversing at least two sectors and six paths crossing Area 2 in some manner.

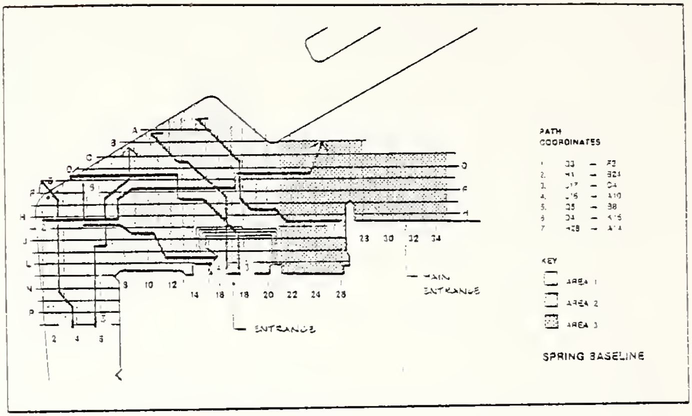
Figure 12 shows the pictoral representation of pedestrian paths for the spring test session. Similar to the baseline period, three paths either begin (paths 2 and 4) or terminate (path 3) at the entrance. The distribution of paths is characterized by three paths traversing two sectors and five paths crossing area 2 (paths 2, 3, 4, 6, and 7). The distribution of paths for both the spring baseline and test sessions is very similar and exhibits no appreciable differences.

In Figure 13 the distribution of high-probability paths is presented for the summer baseline session. It will be noted that four paths either commence (path 6) or exit (paths 3, 4, and 5) at the building entrance. Two paths are encompassed within area 1 (paths 1 and 2) and one path begins in area 3 and exits in area 2 (path 7). Three paths traverse at least two areas (paths 3, 6, and 7), and five paths cross area 2 to some degree.

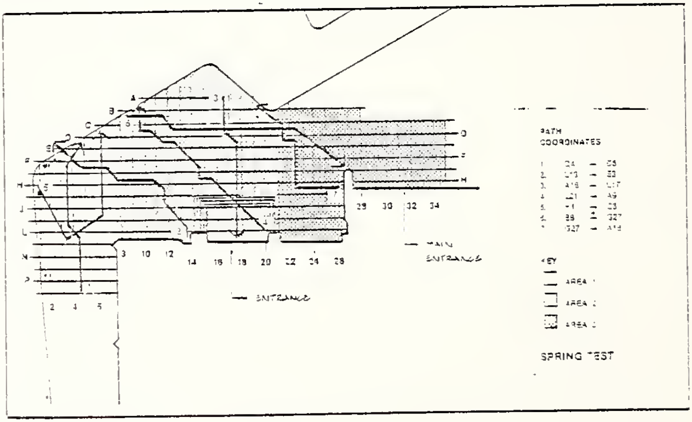
The summer test day (Fig. 14) exhibits a completely

Fig. 11. Site A/Spring Baseline High Probability Paths

Fig. 12. Site A/Spring Test High Probability Paths



SPRING BASELINE



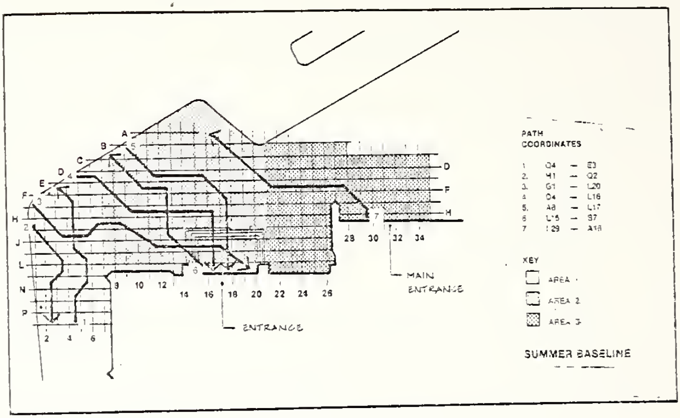
SPRING TEST

STUDY SITE A

PLAYING AREAS & GRID

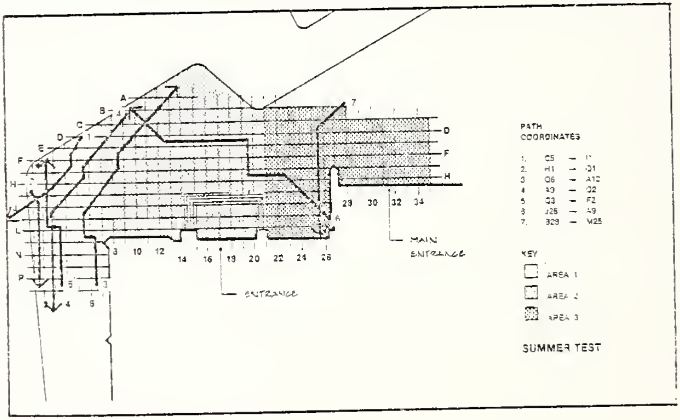
Fig. 13. Site A/Summer Baseline High Probability Paths

Fig. 14. Site A/Summer Test High Probability Paths



1	Q4	—	E3
2.	H1	—	Q2
3.	G1	—	L20
4	D4	—	L16
5.	A8	—	L17
6	L15	—	S7
7	I29	—	A18

SUMMER BASELINE



1.	C5	—	[illegible]
2.	H1	—	Q1
3	Q6	—	A12
4	A3	—	Q2
5	Q3	—	F2
6	J25	—	A9
7.	B29	—	M25

SUMMER TEST

STUDY SITE A
FILMING AREA - 5' GRID

different configuration of paths. None of the seven high-probability paths begin or exit at the building entrance in contrast to the four paths during the baseline session. Three paths are completely bounded by area 1 (paths 1, 2, and 5), and two others either begin (path 3) or terminate (path 4) in area 1. Whereas in the baseline session five paths cross two areas in the test session, compared to the five crossovers in the baseline period. Of the three paths that traverse area 2, only one path (path 6) runs parallel to the building entrance. The other two paths remain on the periphery of area 2. Compared to the test session, the path configuration on the baseline day is much less diffuse.

Velocity, Density, and Behavior.

The analysis of variance for velocity measurements is based upon a sample of thirty subjects from each of six sessions. Significant differences occur for season only (Table 5). The average pedestrian speed for summer (2.6 ft/sec, 0 8 m/sec) is significantly less than spring (3.4 ft/sec, 1.1 m/sec) and winter (3.1 ft/sec, 1.0 m/sec).

Table 6 lists the F ratios for the analysis of variance for pedestrian density. Significant differences are exhibited for season only. The average density for spring (3.6 people/frame) is significantly greater than winter (2.7 people/frame) or summer (3.1 people/frame).

For all seasons there are very few occurrences noted

Table 5

Analysis of Variance of Velocity (Site A)

Source of Variance	Sum of Squares	df	Mean Squares	F Ratio
Season	34.925	2/180	17.462	4.257*
Session	10.686	1/180	10.687	3.820
Season by Session	5.267	2/180	5.267	2.610

$^*p \leq .05$

Table 6

Analysis of Variance of Density (Site A)

Source of Variance	Sum of Squares	df	Mean Squares	F Ratio
Season	33.154	2/234	16.572	3.964*
Session	7.432	1/234	7.432	2.871
Season by Session	6.008	2/234	3.004	.761

*$p \leq .05$

of any of the observational behavior categories (see Table 7). For example, during all six sessions no individuals stood alone in the area.

Density Distribution.

Figure 15 contains the density distribution for the winter baseline period. Similar to the path analysis, the distribution of pedestrians is spread throughout the grid. The density distribution is approximately equally divided among the three areas of the grid. The most frequently counted category is one pedestrian per square. Figure 16 presents the densities for the winter test session. Analogous to the path analysis, the greatest densitites are located in area 1 and area 3. The density is particularly heavy in area 1.

Figures 17 and 18 display the density distributions for the spring baseline and test sessions, respectively. Similar to the path analysis, the densities for both sessions are distributed throughout the grid. For both sessions the most frequently counted category is one pedestrian per square. There is no appreciable difference between the two sessions. This result is similar to the path analysis.

Figures 19 and 20 display the density distributions for the summer baseline and test periods. For the baseline period the distribution is dispersed throughout the grid. For the test session the distribution is located primarily

Table 7

Behavioral Analysis (Site A)

	Winter		Spring		Summer	
	Baseline	Test	Baseline	Test	Baseline	Test
Average number of pedestrians	2.88	2.63	3.85	3.28	3.25	2.95
Highest count	9	8	7	7	7	9
Lowest count	0	0	0	0	0	0
Average walking speed (ft/sec)	2.65	3.65	3.15	3.58	2.21	2.98
Number standing alone	1	1	1	0	2	3
Average time (sec)	10	7.4	5	---	59	47.5

Table 7 (continued)

Behavioral Analysis (Site A)

	Winter		Spring		Summer	
	Baseline	Test	Baseline	Test	Baseline	Test
Number standing groups	2	0	0	0	0	0
Average time (sec)	39	---	---	---	---	---
Number sitting	0	0	0	0	0	0
Average time (sec)	---	---	---	---	---	---
Total number platoons	10	19	13	19	20	14
2 people	8	18	11	17	17	12
3 people	2	1	2	2	3	2
4 people	0	0	0	0	0	0
5 people	0	0	0	0	0	0

Fig. 15. Site A/Winter Baseline Density Distribution

WINTER BASELINE

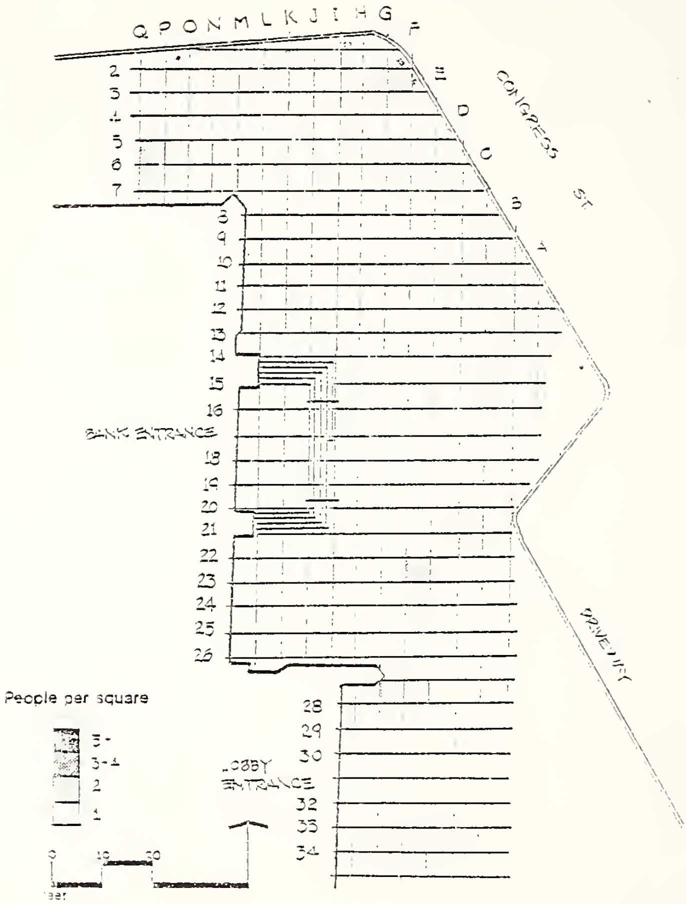
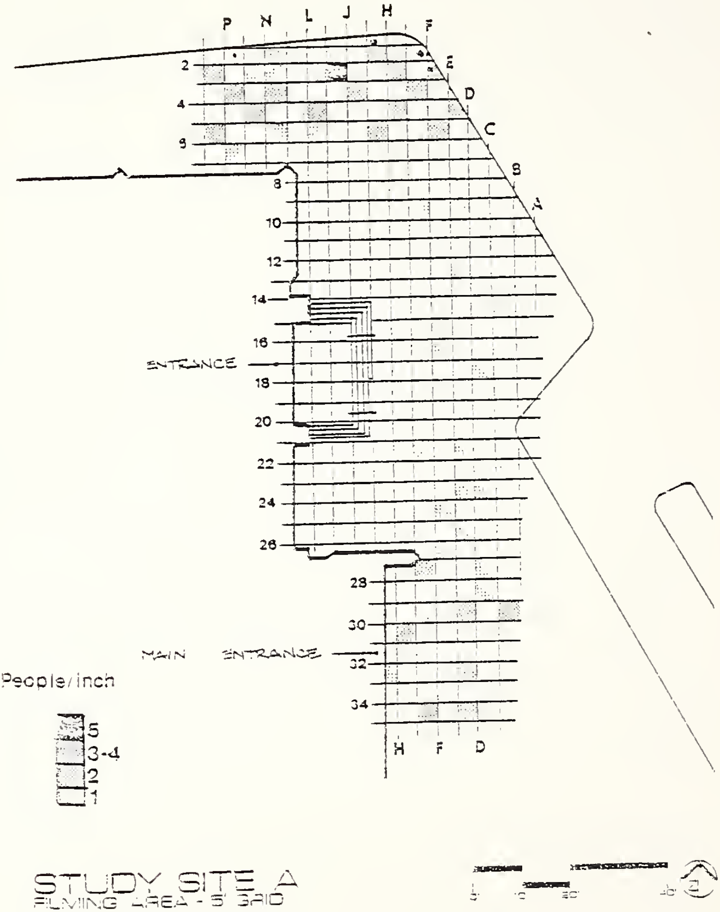


Fig. 16. Site A/Winter Test Density Distribution

WINTER TEST



STUDY SITE A
FILMING AREA - 5' GRID

Fig. 17. Site A/Spring Baseline Density Distribution

SPRING BASELINE

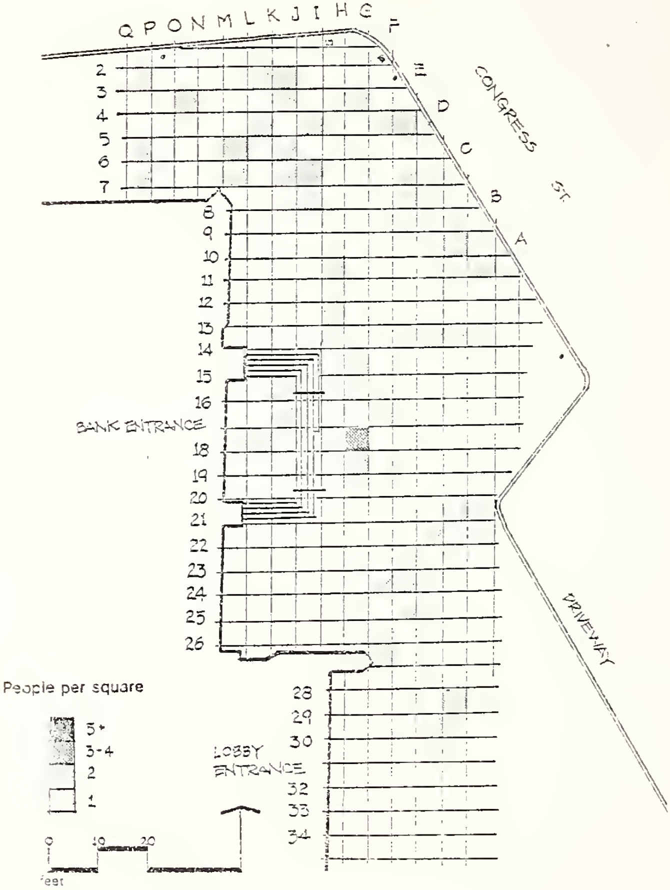


Fig. 18. Site A/Spring Test Density Distribution

SPRING TEST

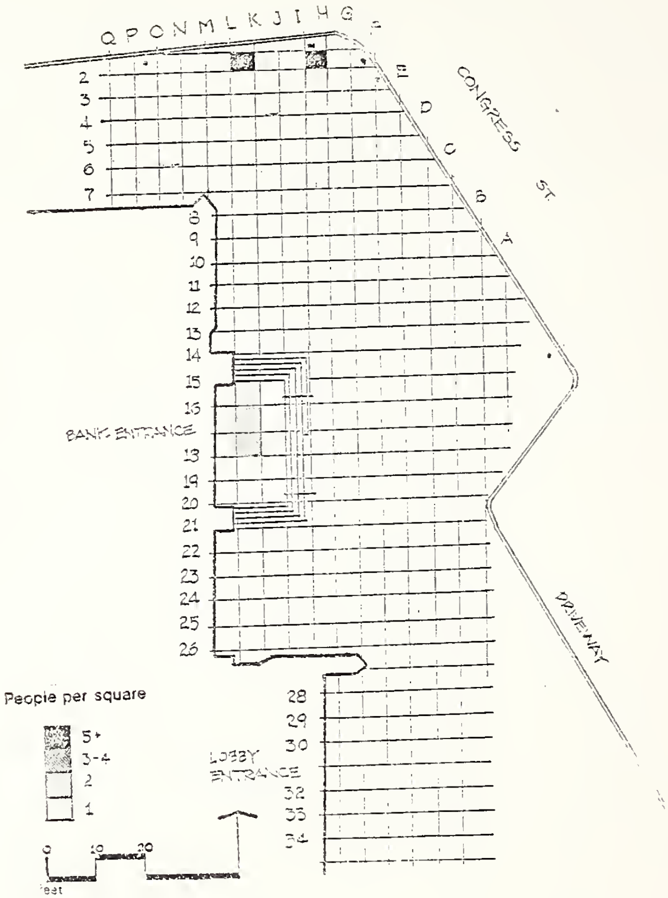

Q P O N M L K J I H G F
E D C B A
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 18 19 20 21 22 23 24 25 26 28 29 30 32 33 34
CONGRESS ST.
DRIVEWAY
BANK ENTRANCE
LOBBY ENTRANCE
People per square
5+
3-4
2
1
0 10 20
feet

Fig. 19. Site A/Summer Baseline Density Distribution

SUMMER BASELINE

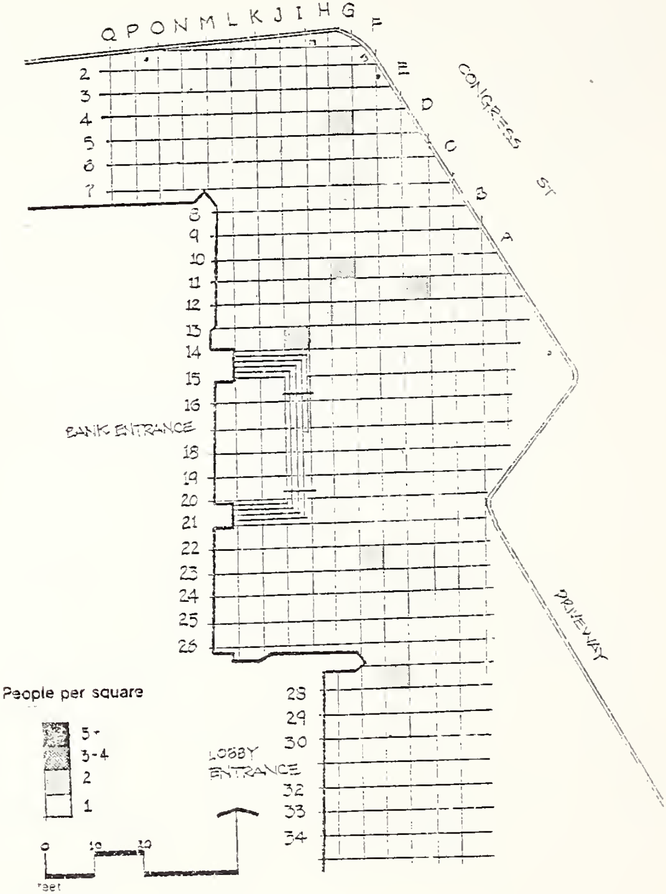
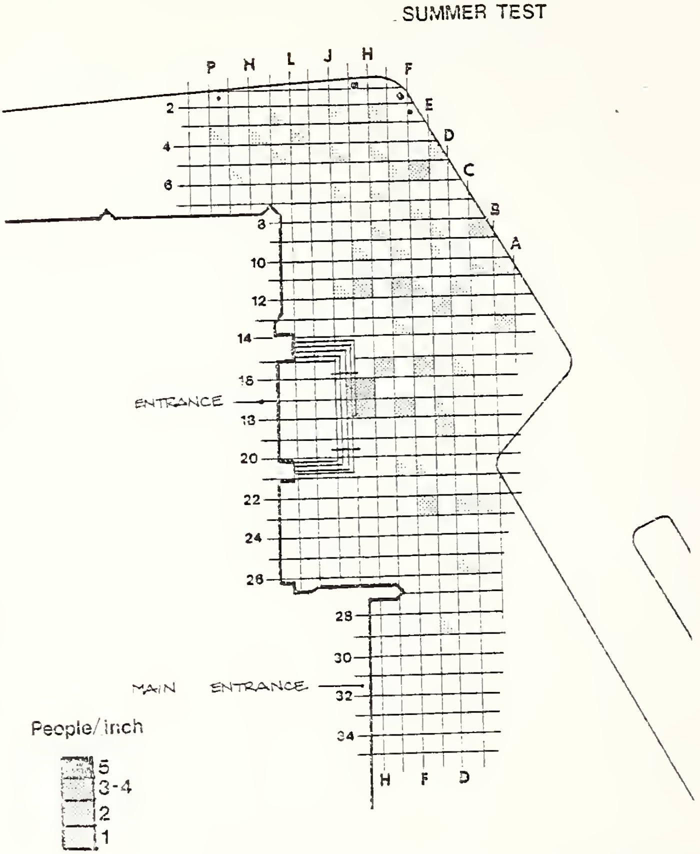


Fig. 20. Site A/Summer Test Density Distribution



STUDY SITE A
FILMING AREA - 5' GRID

in Area 2 which differs from the path analysis.

Site B--600-Foot Office Building.

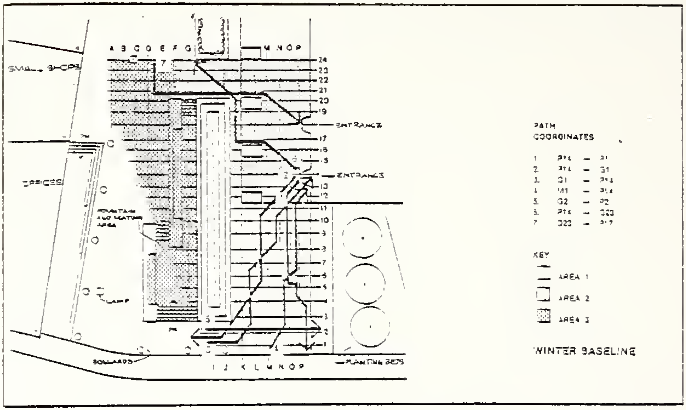
The grid map for the 600-foot (183-meter) office building has been divided into the following three areas: area 1 is a space adjacent to the main entrance of the office building; area 2 is a space adjacent to a secondary entrance and extends to a pathway; and area 3 is bounded by a series of stores and a fountain within the space.

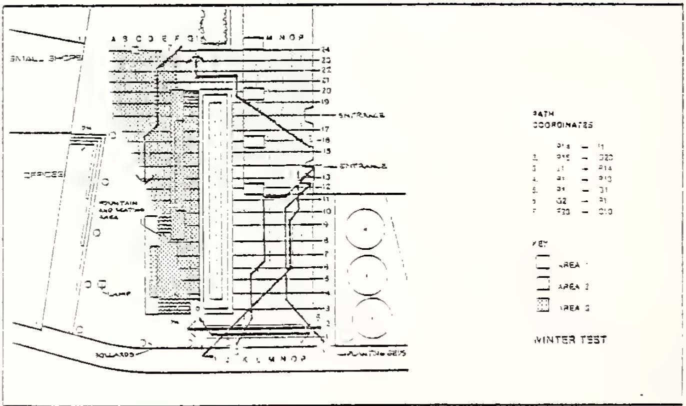
Figure 21 illustrates the distribution of high-probability paths for the winter baseline session. The distinguishing characteristic of this configuration of paths is that five of the paths initiate or terminate at the main entrance (paths 1, 2, 3, 4, and 5). Two paths (paths 1 and 2) begin at the entrance and exit in area 1. Two other paths that begin in area 1 exit at the entrance (paths 3 and 4). Only one path (path 7) traverses two areas.

Figure 22 depicts the distribution of paths for the winter test period. Similar to the baseline session, the principal characteristic of this session is that four paths have endpoints at the building's entrance (paths 1, 2, 3, and 4). Two paths begin at the entrance (paths 1 and 2), and two terminate (paths 1 and 3). Again, one path traverses two distinct areas (path 7). The two remaining paths (paths 5 and 6) are approximately parallel to one another on the periphery of area 1 (paths 5 and 6).

Fig. 21. Site B/Winter Baseline High Probability Paths

Fig. 22. Site B/Winter Test High Probability Paths


A B C D E F G
M N O P
SMALL SHOPS
OFFICES
FOUNTAIN AND SEATING AREA
LAMP
BOLLARDS
PLANTING BEDS
ENTRANCE
ENTRANCE
24
23
22
21
20
19
17
16
15
13
12
11
10
9
8
7
6
5
3
2
1
I J K L M N O P
PATH COORDINATES
1 P14 — J1
2. P14 — G1
3. G1 — P14
4 M1 — P14
5. G2 — P2
6. P14 — G23
7 G23 — P17
KEY
AREA 1
AREA 2
AREA 3
WINTER BASELINE


A B C D E F G
M N O P
SMALL SHOPS
OFFICES
FOUNTAIN AND SEATING AREA
LAMP
BOLLARDS
PLANTING BEDS
ENTRANCE
ENTRANCE
24
23
22
21
20
19
17
16
15
13
12
11
10
9
8
7
6
5
3
2
1
I J K L M N O P
PATH COORDINATES
P14 — I1
2. P15 — G20
3 J1 — P14
4. A1 — P13
5. A1 — G1
6 G2 — A1
7 F20 — O10
KEY
AREA 1
AREA 2
AREA 3
WINTER TEST

STUDY SITE 3

[illegible]

For the spring baseline session (Figure 23), five high probability paths again have endpoints at the principal entrance (paths 1, 2, 3, 4, and 5). Three paths commence (paths 1, 2, and 3) and two exit (paths 4 and 5) at this point. The path distribution for the spring test session (Figure 24) is analogous to the baseline period. Four principal paths begin (paths 1, 2, and 6) or end (path 3) at the entrance. Two paths (paths 4 and 5) run parallel at the periphery of area 1, and one traverses (path 7) two areas.

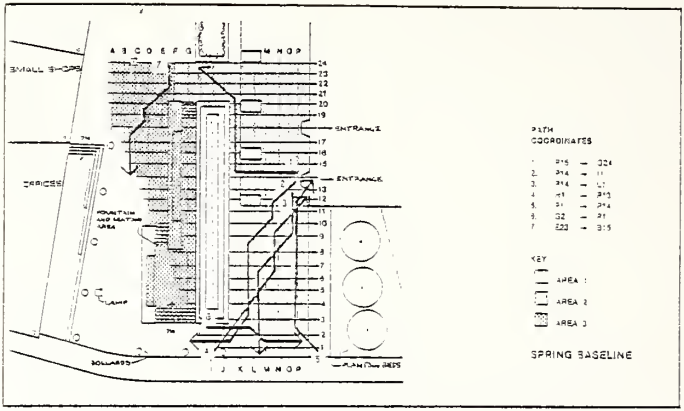
The summer baseline (Figure 25) and the test sessions (Figure 26) show similar patterns relative to the other two sessions. In both sessions the five highest probability paths enter or exit at the bank entrance. Likewise, in both sessions one path crosses areas 2 and 3, and one path is enclosed in area 3.

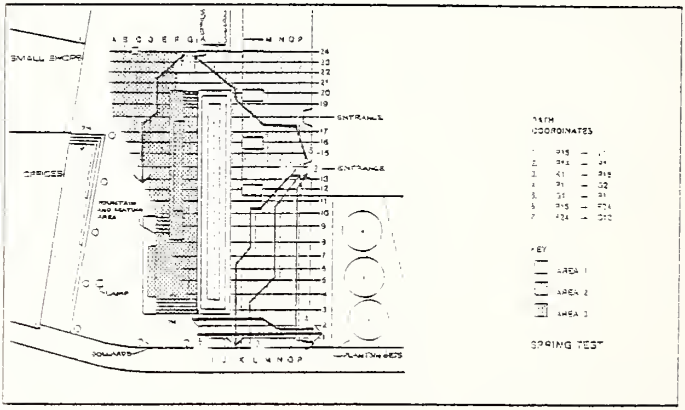
Velocity, Density, and Behavior.

The analysis of variance of pedestrian velocity shows significant effects for season (Table 8). Velocity is significantly less during summer (2 4 ft/sec, 0.7 m/sec) than spring 3.1 ft/sec, 1.0 m/sec) or winter (3.4 ft/sec, 1.1 m/sec). Density (Table 9) and behavioral analysis (Table 10) reveal that the density for summer (7.5 people/frame) is greater than winter (3.7 people/frame) and spring (5.4 people/frame).

Fig. 23. Site B/Spring Baseline High Probability Paths

Fig. 24. Site B/Spring Test High Probability Paths

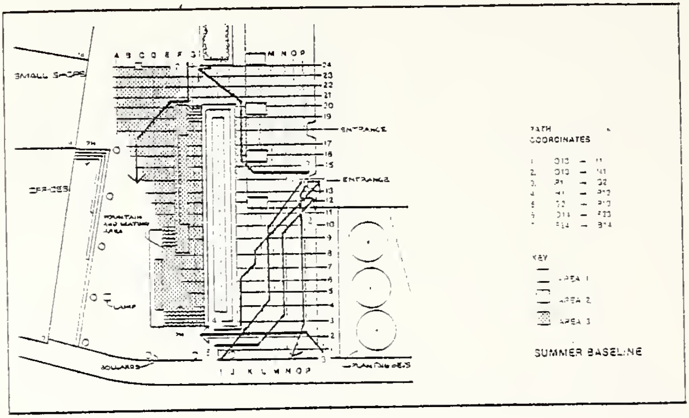


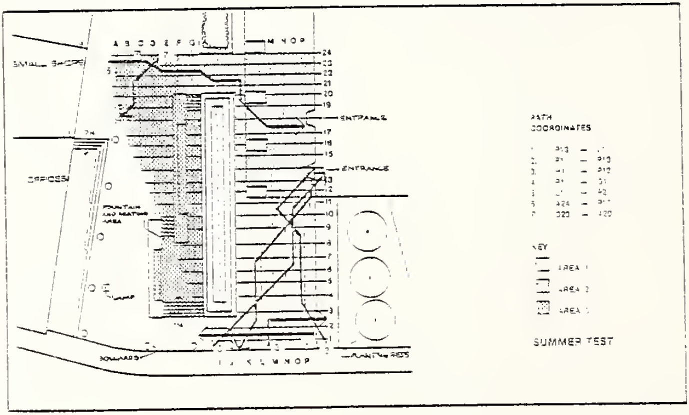


STUDY SITE 3
FILMING AREA - 5' GRID

Fig. 25. Site B/Summer Baseline High Probability Paths

Fig. 26. Site B/Summer Test High Probability Paths





STUDY SITE 3
PLAYING AREA - [illegible]

Table 8

Analysis of Variance of Velocity (Site B)

Source of Variance	Sum of Squares	df	Mean Squares	F Ratio
Season	46.137	2/180	23.065	6.321**
Session	12.643	1/180	12.643	3.618
Season by Session	14.226	2/180	7.113	1.981

$^{**}p \leq .01$

Table 9

Analysis of Variance of Density (Site B)

Source of Variance	Sum of Squares	df	Mean Squares	F Ratio
Season	26.321	2/234	13.112	3.601*
Session	2.178	1/234	2.178	.743
Season by Session	3.219	2/234	1.609	.398

$^{*}p \leq .05$

Table 10

Behavioral Analysis (Site B)

	Winter		Spring		Summer	
	Baseline	Test	Baseline	Test	Baseline	Test
Average number of pedestrians	4.18	3.20	3.98	6.91	7.03	8.05
Highest count	8	5	6	8	11	14
Lowest count	0	0	1	0	1	1
Average walking speed (ft/sec)	3.21	3.68	2.86	3.33	2.21	2.63
Number standing alone	3	2	1	0	6	2
Average time (sec)	8	4	16	---	34	26

Table 10 (continued)

Behavioral Analysis (Site B)

	Winter		Spring		Summer	
	Baseline	Test	Baseline	Test	Baseline	Test
Number standing groups	0	0	0	0	0	0
Average time (sec)	---	---	---	---	---	---
Number sitting	0	0	0	0	0	0
Average time (sec)	---	---	---	---	---	---
Total number platoons	35	16	28	39	37	29
2 people	30	15	26	31	33	24
3 people	4	1	1	8	3	4
4 people	0	0	0	0	1	1
5 people	1	0	1	0	0	0

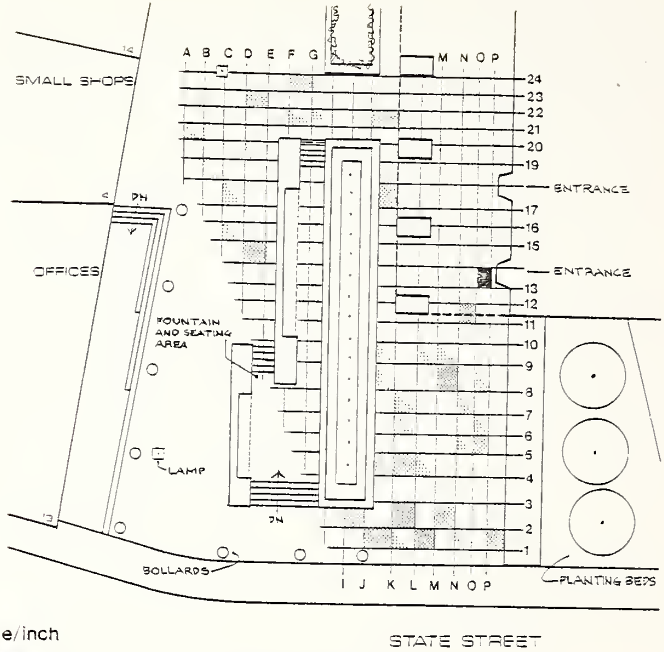
Density Distribution.

Figures 27 and 28 display the winter baseline and test sessions, respectively. For both sessions the highest densities are located in area 1 adjacent to the main thoroughfare and the entrance of the building. This density pattern mirrors the distribution of high probability paths. In both periods the most frequent category is one pedestrian per square. However, both sessions also display densities of 2 to 4 individuals per square. For both sessions, Area 3 also shows moderate densities. (For all sessions for this building, area 2 was blocked from the camera. Therefore no densities are recorded in this area for any of the sessions.)

Figures 29 and 30 display the spring baseline and test sessions. Analogous to the path distribution, the greatest densities are located in area 1. Compared to the winter sessions the densities per square are significantly greater. In the test session, five squares show densities greater than three, and four squares display densities of two. For the baseline period two squares have densities greater than three and eight squares have densities of two. For area 3 both sessions also show greater densities than the winter sessions.

Figures 31 and 32 display the summer baseline and test periods. The density patterns are similar to the other two seasons.

Fig. 27. Site B/Winter Baseline Density Distribution



People/inch

- ▩ 5
- ▨ 3-4
- ▧ 2
- ☐ 1

WINTER BASELINE

STUDY SITE B

FILMING AREA - 5' GRID

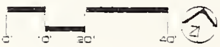
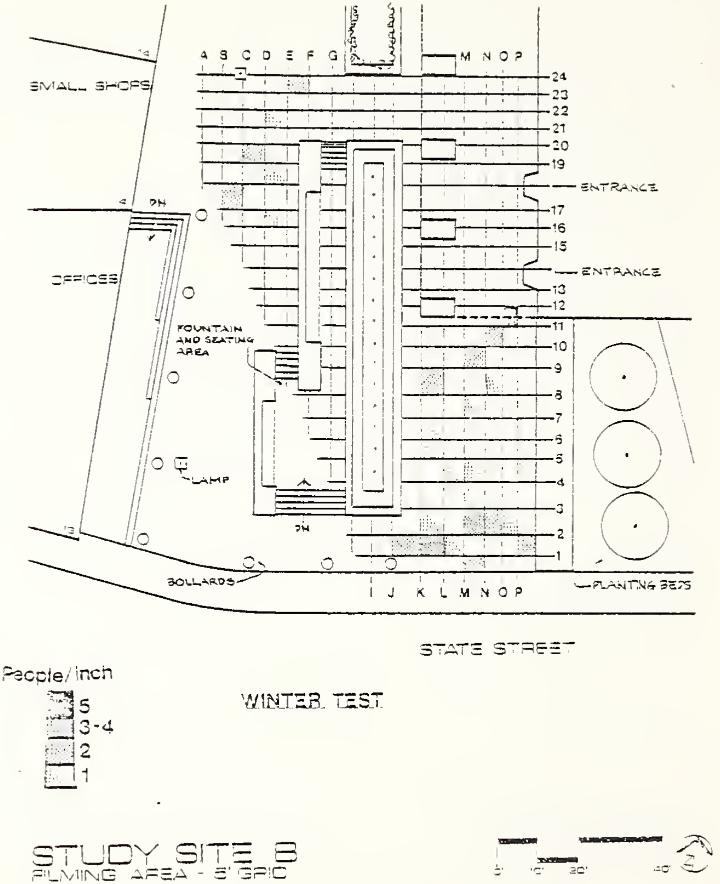
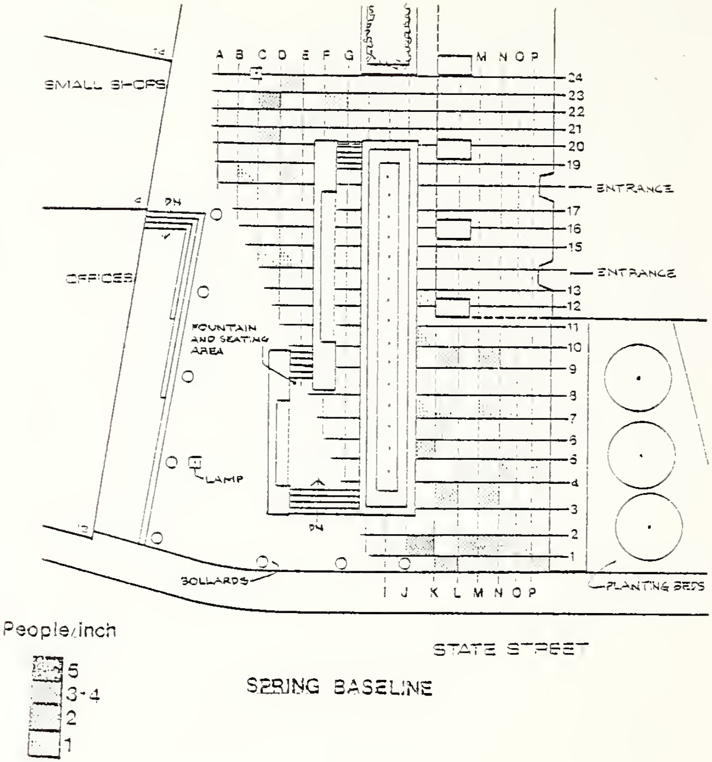


Fig. 28. Site B/Winter Test Density Distribution



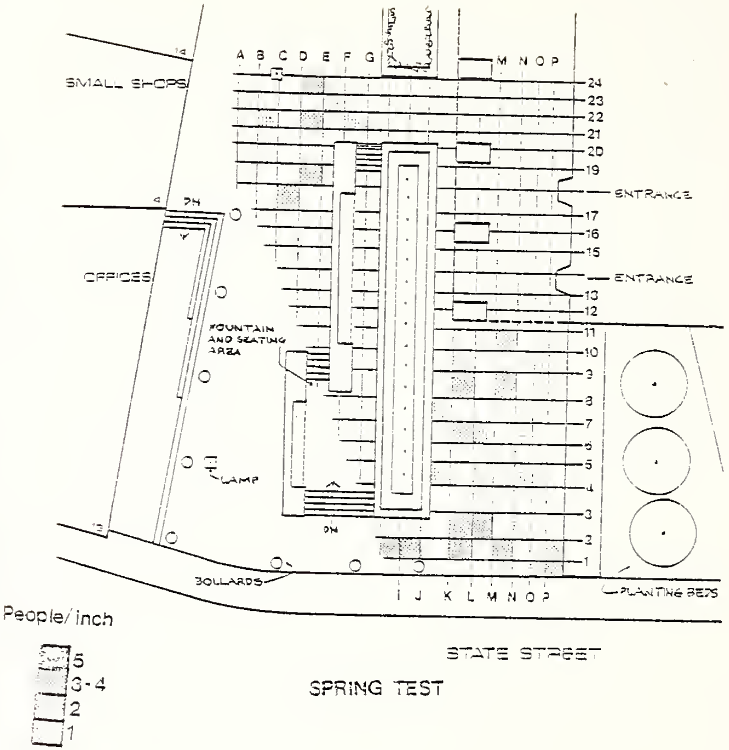
STUDY SITE B
FILMING AREA - 5' GRID

Fig. 29. Site B/Spring Baseline Density Distribution



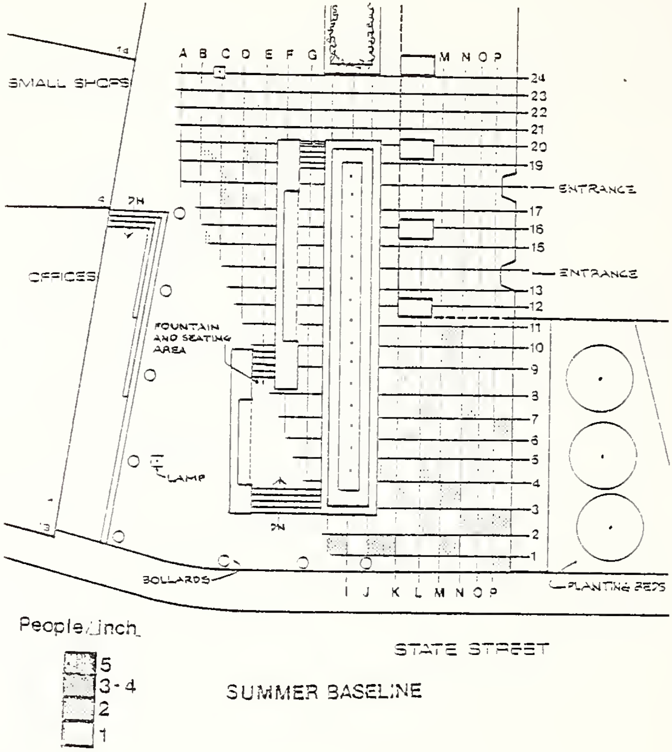
STUDY SITE B
FILMING AREA - 5' GRID

Fig. 30. Site B/Spring Test Density Distribution



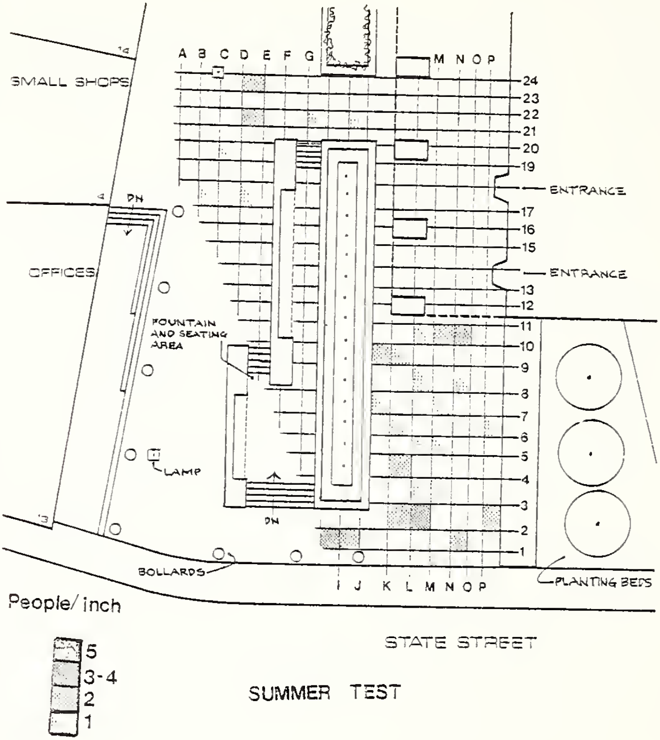
STUDY SITE B
FILMING AREA - 5' GRID

Fig. 31. Site B/Summer Baseline Density Distribution



STUDY SITE 3
FILMING AREA - 5' GRID

Fig. 32. Site B/Summer Test Density Distribution



SUMMER TEST

STUDY SITE B
FILMING AREA - 5' GRID

Site C--City Hall Plaza.

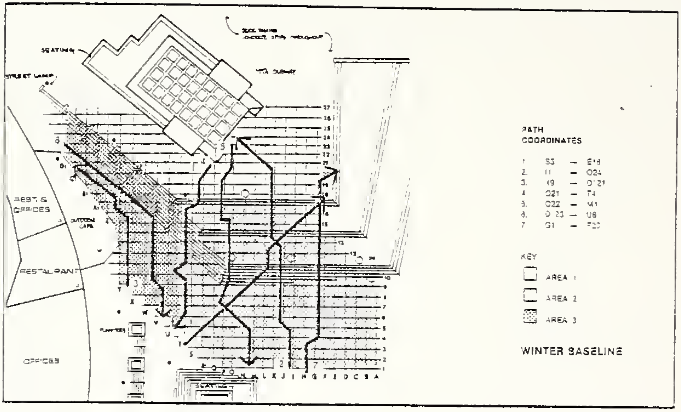
The grid map for City Hall Plaza has also been divided into three distinct areas for descriptive purposes. Area 1 is adjacent to the subway station and bounded by the first level of plaza stairs. Area 2 is adjacent to the building's entrance, and area 3 is a major walkway leading to the building and bounded by a set of stairs in the mall and by a series of cafes and shops.

Figure 33 depicts the baseline session for winter. Three paths either begin (paths 4 and 5) or exit (path 2) at the subway station building. Two paths are completely encompassed within area 3, one starting (Path 3) and one terminating (Path 6) at the building. Finally, two paths begin in area 2 at City Hall and exit in area 1 (paths 1 and 7). Five paths cross over from area 1 to area 2 or vice versa (paths 1, 2, 4, 5, and 7).

For the winter test session, the distribution of paths is depicted in Figure 34. Two paths initiate at the subway station (paths 2 and 7), but in contrast to the baseline period in which they exit at City Hall, these paths terminate within area 1. Three paths are totally encompassed within area 1, two beginning at City Hall (paths 4 and 6) and one exiting at the building (path 5). In contrast to the baseline session where five paths cross at least two areas, only two paths traverse two areas during this session (paths 1 and 3). Five paths are

Fig. 33. Site C/Winter Baseline High Probability Paths

Fig. 34. Site C/Winter Test High Probability Paths



PATH
COORDINATES

1	S3	—	E18
2.	I1	—	O24
3.	X9	—	O'21
4	O21	—	T4
5.	O22	—	M1
6.	O'23	—	U8
7	G1	—	F20

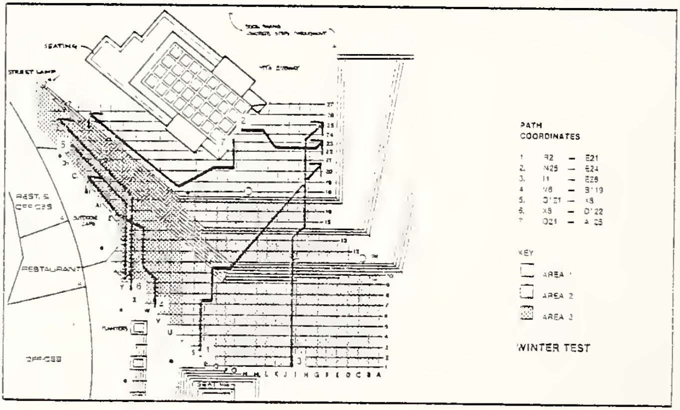
KEY

☐ AREA 1

☐ AREA 2

▨ AREA 3

WINTER BASELINE



PATH
COORDINATES

1	R2	—	E21
2.	N25	—	E24
3.	I1	—	E25
4	V8	—	B'19
5.	O'21	—	X8
6.	X8	—	O'22
7	O21	—	A'23

KEY

☐ AREA 1

☐ AREA 2

▨ AREA 3

WINTER TEST

STUDY SITE C
PLANTING AREA + B GRID

completely bounded in either area 1 or 3 (paths 2, 4, 5, 6, and 7). The configuration of paths is more concentrated within geographical areas than in the baseline period, leading to a distribution of paths that is more structured.

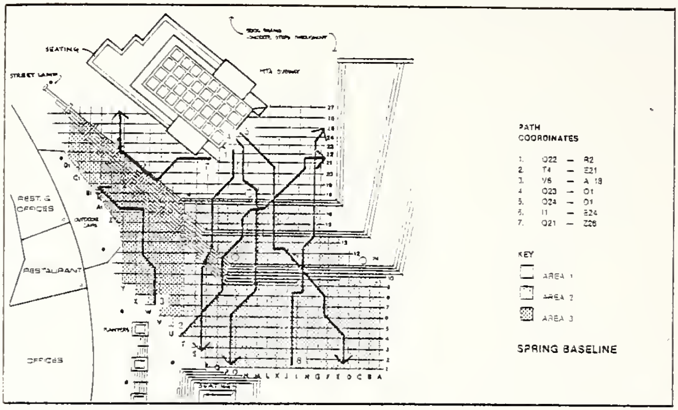
Figure 35 illustrates the distribution of paths for the spring baseline session. Four paths commence from the subway station (paths 1, 4, 5, and 7). Three of these paths (1, 4, and 5) terminate in area 2, and one path (path 7) is encompassed within area 1. One path (path 3) is enclosed within area 3 and two paths (paths 2 and 6) begin in area 2 and exit in area 1. Five of the seven paths traverse at least two distinct areas (paths 1, 2, 4, 5, and 6).

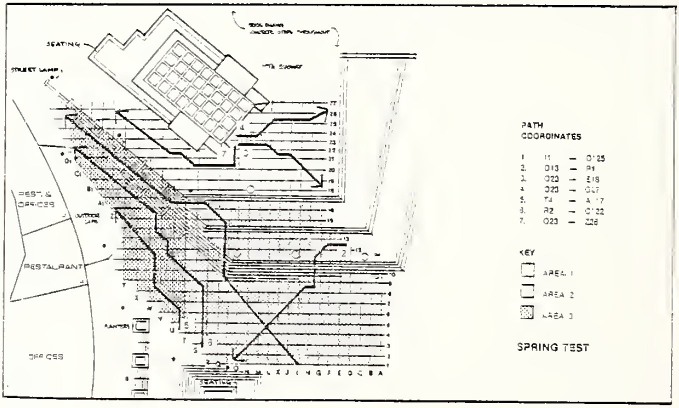
The spring test session is portrayed in Figure 36. Three paths commence at the subway station (paths 3, 4, and 7), but in contrast to the baseline period all of these paths remain within the boundaries of area 1. One path is completely enclosed within area 3 (path 5) and one within area 2 (path 2). Two other paths begin in area 2 and terminate in area 3 (paths 1 and 6). Unlike the baseline session, five paths remain enclosed within one area (paths 2, 3, 4, 5, and 7) and only two paths (paths 1 and 6) traverse two areas. The test period is more structured than the baseline session, with more paths contained within one area.

Figure 37 depicts the distribution of paths for the summer baseline session. Two paths (paths 2 and 7) enter

Fig. 35. Site C/Spring Baseline High Probability Paths

Fig. 36. Site C/Spring Test High Probability Paths

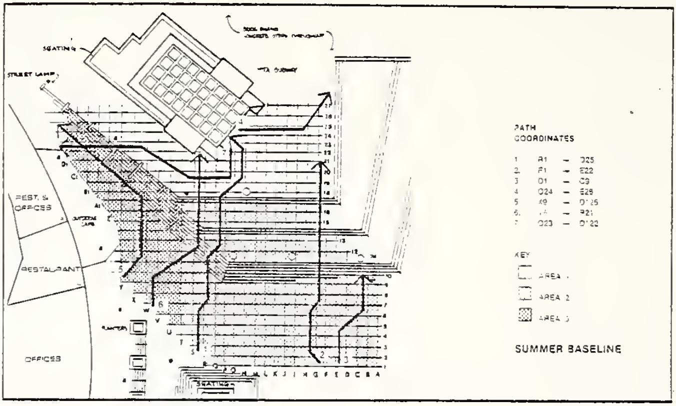




STUDY SITE C
FILMING AREA - 5' GRID

Fig. 37. Site C/Summer Baseline High Probability Paths

Fig. 38. Site C/Summer Test High Probability Paths



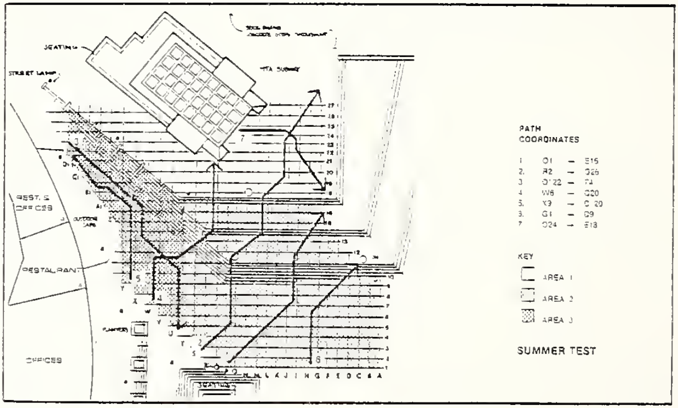
PATH
COORDINATES

1	R1	–	D25
2.	F1	–	E22
3	O1	–	C9
4	O24	–	E28
5	X9	–	O'25
6.	[illegible]	–	P21
7	O23	–	O'22

KEY

▢ AREA 1
⬚ AREA 2
▩ AREA 3

SUMMER BASELINE



PATH
COORDINATES

1	O1	–	E15
2.	R2	–	O26
3	O'22	–	T4
4	W6	–	O20
5.	X9	–	C 20
6.	G1	–	D9
7	O24	–	E13

KEY

▢ AREA 1
⬚ AREA 2
▩ AREA 3

SUMMER TEST

STUDY SITE C
FILMING AREA · 5' GRID

at the subway station and two paths (paths 1 and 6) exit there. Two paths are enclosed within one of two areas--one path in area 2 (path 3) and one in area 3 (path 5). Four paths traverse at least two areas (paths 1, 2, 6, and 7).

For the summer test session (Figure 38) two paths are enclosed within area 3 (paths 3 and 5), two within area 2 (paths 1 and 6), and one within area 1 (path 7). Two paths traverse at least two areas (paths 2 and 4). The distribution of paths is similar to the baseline period.

Velocity, Density, and Behavior.

An analysis of variance for velocity shows a significant effect for season and session (see Table 11). The average pedestrian velocity for winter (3.0 ft/sec, 0.9 m/sec) is significantly greater than spring (2.6 ft/sec, 0.8 m/sec) and summer (2.4 ft/sec, 0.75 m/sec). Average velocity for baseline periods across seasons (2 5 ft/sec, 0.8 m/sec) is significantly less than test periods (2.9 ft/sec, 0.9 m/sec).

The density analysis reveals a significant difference from one season to another. The summer density (33.4 people/frame) is significantly greater than spring (26.0 people/frame) or winter (13.6 people/frame) (see Table 12).

Analysis of the behavioral data (sitting and standing) shows that the determining factor affecting the frequency of these behaviors is the season of the year (see Table 13).

Table 11

Analysis of Variance of Velocity (Site C)

Source of Variance	Sum of Squares	df	Mean Squares	F Ratio
Season	21.068	2/180	15.534	5.231**
Session	19.381	1/180	19.381	6.460*
Season by Session	1.283	2/180	.643	.328

*$p \leq .05$
**$p \leq .01$

Table 12

Analysis of Variance of Density (Site C)

Source of Variance	Sum of Squares	df	Mean Squares	F Ratio
Season	19.538	2/234	9.769	7.281**
Session	4.427	1/234	4.427	2.261
Season by Session	4.721	2/234	2.361	.987

$^{**}p \leq .01$

Table 13

Behavioral Analysis (Site C)

	Winter		Spring		Summer	
	Baseline	Test	Baseline	Test	Baseline	Test
Average number of pedestrians	14.20	12.68	30.80	21.25	40.28	26.55
Highest count	22	21	50	46	46	53
Lowest count	2	4	21	6	12	10
Average walking speed (ft/sec)	2.89	3.22	2.46	2.79	2.13	2.71
Number standing alone	5	3	20	3	27	13
Average time (sec)	16	10	36	7	40	60

Table 13 (continued)

Behavioral Analysis (Site C)

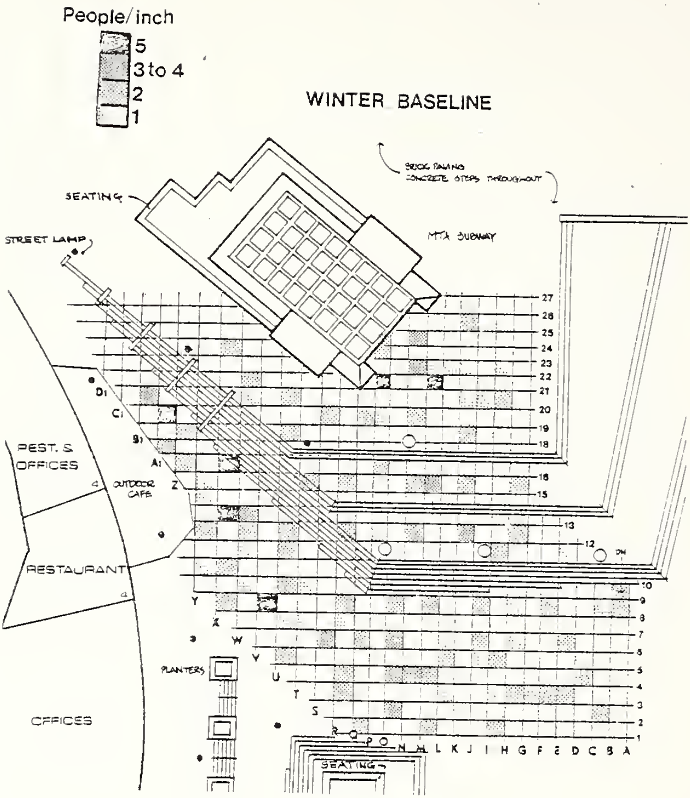
	Winter		Spring		Summer	
	Baseline	Test	Baseline	Test	Baseline	Test
Number standing groups	13	10	22	35	39	35
Average time (sec)	43	27	50	28	42	48
Number sitting	0	0	8	4	18	6
Average time (sec)	---	---	291	340	280	15
Total number platoons	93	90	137	103	151	88
2 people	80	74	119	74	121	77
3 people	8	3	14	15	16	8
4 people	4	11	3	10	12	2
5 people	1	1	1	4	2	1

Both baseline and test sessions in spring and summer have significantly greater behavioral activity than winter. The same relationship is also true for pedestrian platooning.

Density Distribution.

For the density distribution maps for City Hall Plaza (Site C), the distribution of pedestrians is very diffuse throughout the grid map. Since this area is a heavily used plaza, the density distributions do not provide a sensitive indicator for distinguishing between test and baseline sessions. In these maps, the density per square is a more accurate indicator for distinguishing flow characteristics. Figure 39 displays the density distribution for the winter baseline session. It should be noted that the highest densities are located in Area 3 (e.g., a major walkway leading to the building and bounded by a set of stairs in the mall and a series of cafes and shops). In area 3, four squares have densities of 5 people/square, two have 3-4 people/square, and ten have a density of 2 people/frame. Area 2 (adjacent to the building's entrance) is an area of more moderate density [3 squares (3-4 people/square) and 19 squares (2 people/frame)]. Area 1 (adjacent to the subway station and bounded by the first level of plaza stairs) is also an area of relatively more moderate densities. Figure 40 displays the density distribution for the winter test session. Area 3 shows the highest

Fig. 39. Site C/Winter Baseline Density Distribution



STUDY SITE C
FILMING AREA - 5' GRID

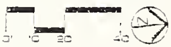
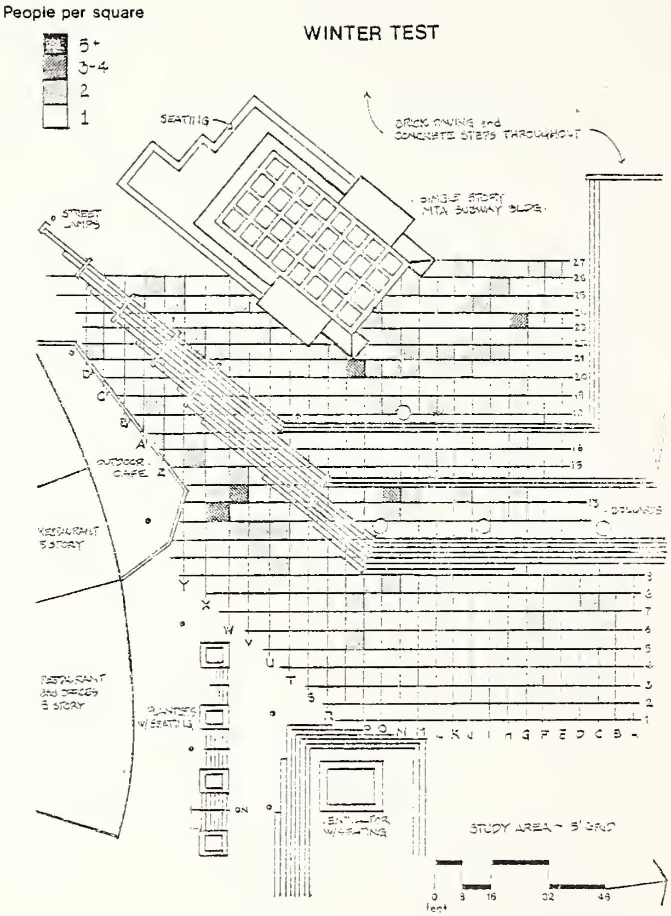


Fig. 40. Site C/Winter Test Density Distribution


People per square
5+
3-4
2
1
WINTER TEST
SEATING
BRICK PAVING and CONCRETE STEPS THROUGHOUT
SINGLE STORY MTA SUBWAY BLDG.
STREET LAMPS
OUTDOOR CAFE
RESTAURANT 5 STORY
RESTAURANT and OFFICES 5 STORY
PLANTERS W/ SEATING
ON
VENTILATOR W/SEATING
BOLLARDS
STUDY AREA ~ 5' GRID
0
8
16
32
48
feet
A B C D E F G H I J K L M N O P
Q R S T U V W X Y Z A' B' C' D'
1 2 3 4 5 6 7 8 9 13 15 16 18 19 20 21 22 23 24 25 26 27

densities though they are less than the baseline period (2 squares--3-4 people/square, 9 squares--2 people/square) Area 2 displays the lowest densities (5 squares-2 people/frame). Finally, Area 1 is a space of relatively moderate density but less than the baseline period. This area shows 3 squares with 3-4 people/square and six squares with 2 people/frame.

Figure 41 displays the spring baseline session density distribution. Area 1 is the space of highest density during this session (1 square--5 people/square, 7 squares--3-4 people/frame, and 8 squares--2 people/square). Area 3 displays the second highest density in this session (6 squares--3-4 people/square and 8 squares--2 people/square). For the spring test session (Figure 42), Area 3 is the highest density space (6 squares--3-4 people/square and 10 squares--2 people/square). This density approximates the baseline session. Area 2 shows a higher density than the baseline period. The distribution for this area is as follows: 1 square--3-4 people/square and 8 squares--2 people/square. Area 3 for the test session approximates the baseline session (8 squares--3-4 people/square and 9 squares--2 people/square).

Figure 43 displays the summer baseline densities. Area 1 is the space of highest density (2 squares--5 people/square, 5 squares--3-4 people/square, and 12 squares--2 people/square). Area 3 exhibits the second highest densi-

Fig. 41. Site C/Spring Baseline Density Distribution

SPRING BASELINE

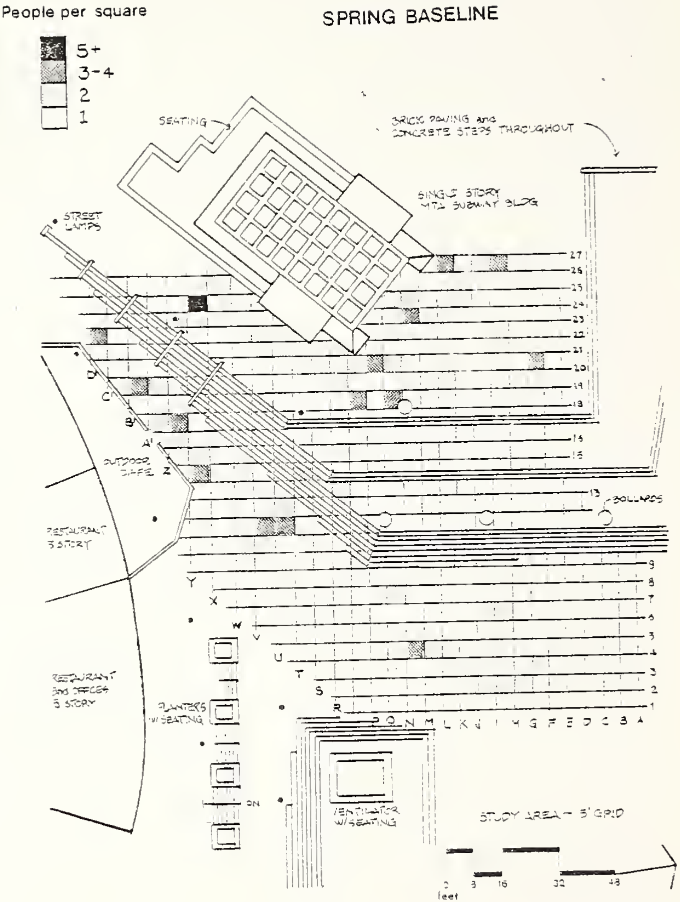


Fig. 42. Site C/Spring Test Density Distribution

SPRING TEST

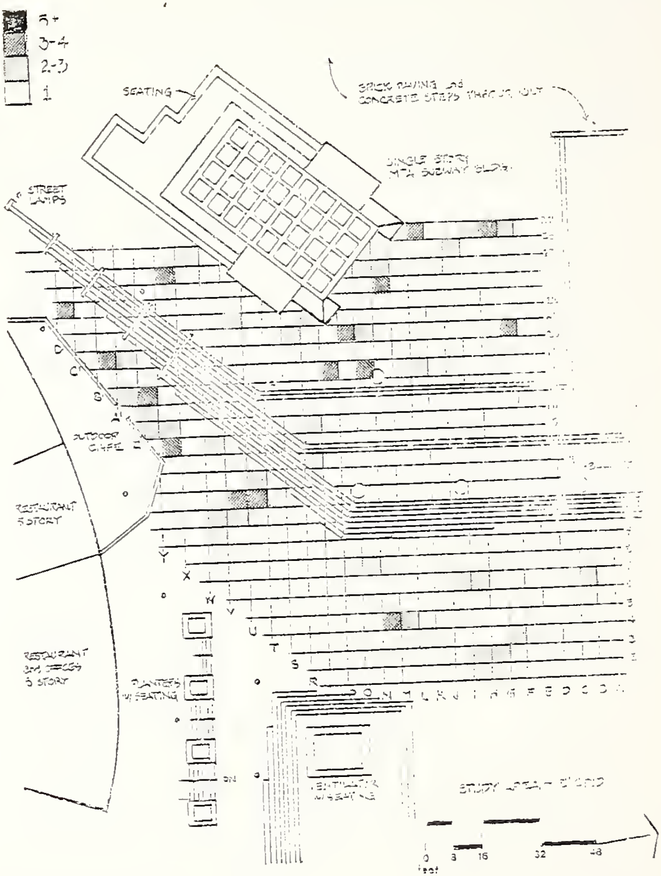
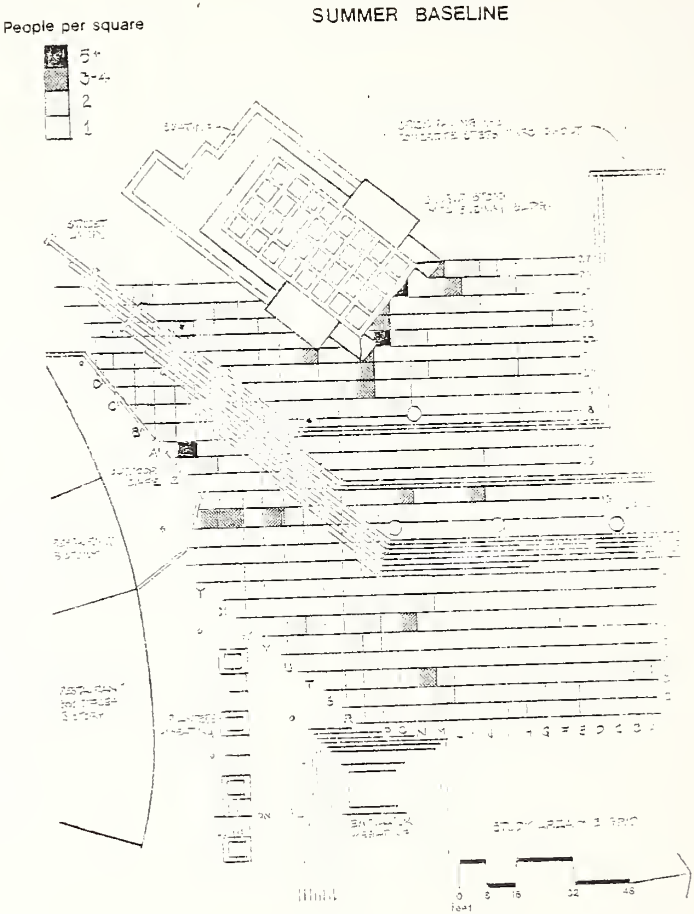

5+
3-4
2-3
1
SEATING
BRICK PAVING AND
CONCRETE STEPS THROUGHOUT
SINGLE STORY
WITH SUBWAY BLDG.
STREET
LAMPS
D
C
B
A
OUTDOOR
CAFE
RESTAURANT
5 STORY
Y
X
W
V
U
T
S
R
RESTAURANT
AND OFFICES
5 STORY
PLANTERS
W/ SEATING
DN
Q P O N M L K J I H G F E D C B A
ENTRANCE
W/ SEATING
STUDY AREA - 8' GRID
0
8
16
32
48
feet

Fig. 43. Site C/Summer Baseline Density Distribution

SUMMER BASELINE



ties (1 sqaure--5 people/square, 5 squares--3-4 people/square, and 7 squares--2 people/frame). Area 2 is the space of relatively modest density. In contrast, Area 3 exhibits the highest density (Figure 44): 1 square--5 people/square, 3 squares--3-4 people/square, 10 squares--2 people/square). Area 1 also exhibits relatively high densities (4 squares--3-4 people/square and 12 squares--2 people/square). Area 1 displays a relatively moderate density (3 squares--3-4 people/square and 7 squares--2 people/square).

Site D--Boston Commons.

This particular grid map is partitioned into three areas relative to a circular fountain that dominates this space (see Figure 45). Area 1 is located adjacent to a main thoroughfare and is bounded by the fountain. Area 2 is adjacent to the fountain, and area 3 encompasses a space that opens into several park pathways. It is bounded by the fountain on one of its edges.

For the winter periods (Figure 45), six of the high-probability paths have one of their endpoints in area 1. Three paths are completely enclosed within the area (paths 1, 2, and 4). Of the two paths that begin in area 3, one terminates in area 1 (path 6) and the other ends within area 3 (path 7). The remaining path begins in area 2 and exits in area 1 (path 5).

Fig. 44. Site C/Summer Test Density Distribution

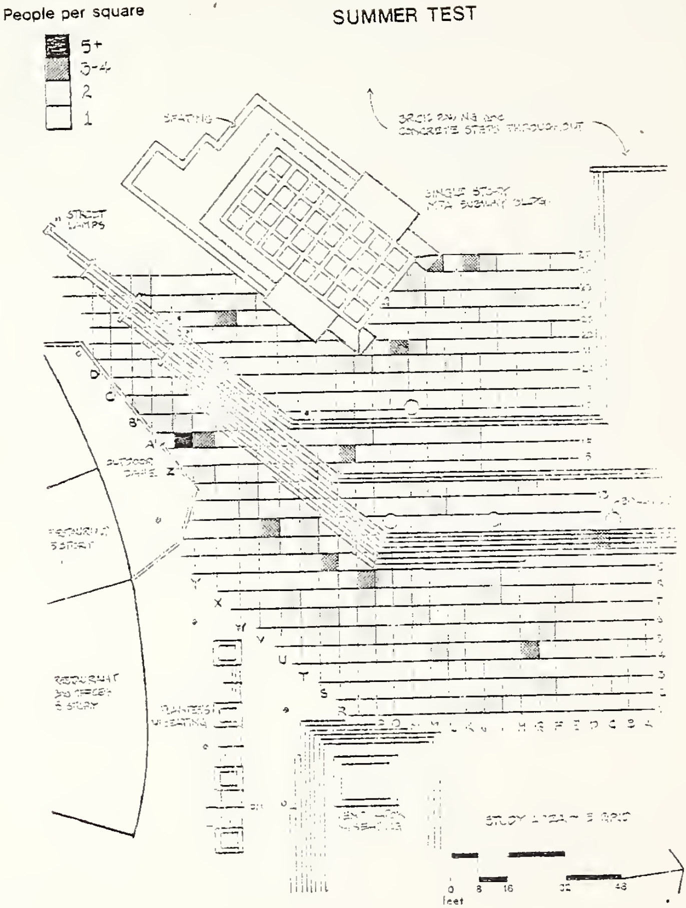
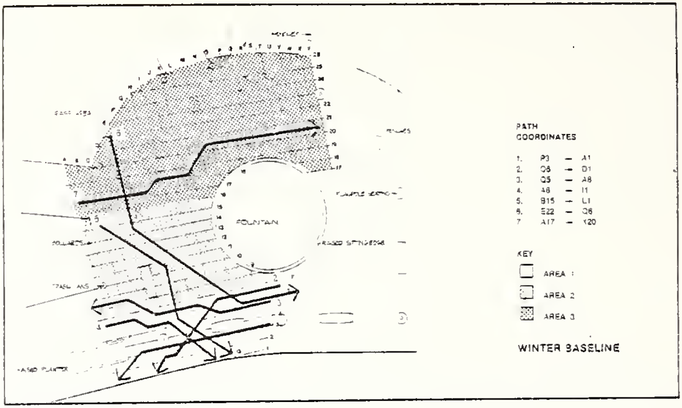

SUMMER TEST
People per square
5+
3-4
2
1
SEATING
BRICK PAVING AND CONCRETE STEPS THROUGHOUT
SINGLE STORY MTA SUBWAY BLDG.
STREET LAMPS
OUTDOOR CAFE
RESTAURANT 3 STORY
RESTAURANT AND OFFICES 3 STORY
PLANTERS WITH SEATING
STUDY AREA AND GRID
D
C
B
A
Z
Y
X
W
V
U
T
S
R
0
8
16
32
48
feet

Fig. 45. Site D/Winter Baseline High Probability Paths

Fig. 46. Site D/Winter Test High Probability Paths



PATH COORDINATES

1.	P3	—	A1
2.	O6	→	D1
3.	Q5	—	A8
4.	A8	—	I1
5.	B15	→	L1
6.	E22	—	Q6
7	A17	—	X20

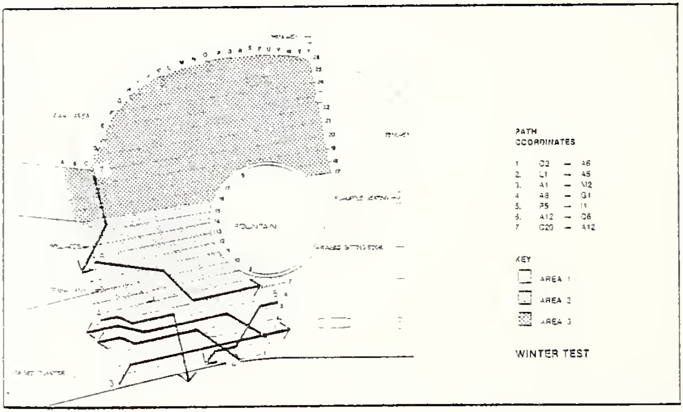
KEY

☐ AREA 1

☐ AREA 2

▨ AREA 3

WINTER BASELINE



PATH COORDINATES

1	O2	—	A6
2.	L1	→	A5
3.	A1	—	M12
4	A8	—	G1
5.	P5	—	I1
6.	A12	—	Q6
7	G20	—	A12

KEY

☐ AREA 1

☐ AREA 2

▨ AREA 3

WINTER TEST

STUDY SITE D
FILMING AREA • 4 GRID

The winter test session (Figure 46) has a distribution of paths similar to the baseline period. Five paths have endpoints within area 1 with four paths enclosed within the area (paths 1, 2, 3, and 5). Only two paths traverse two distinct areas (paths 4 and 7). The only appreciable difference between the two sessions is that there are fewer paths in areas 1 and 2 during the test period.

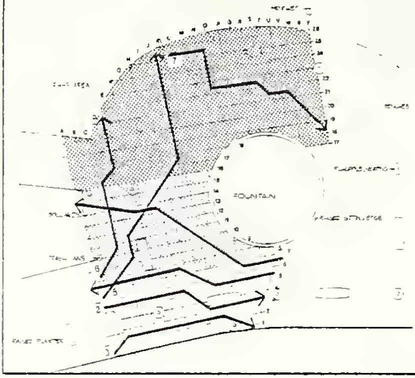
The spring baseline session (Figure 47) displays a high percentage of paths traversing at least two areas. Five of the seven paths cross at least two areas, signifying a broad range of pedestrian movement (paths 1, 4, 5, 6, and 7). Although five paths are initiated in area 1, only two paths exit within this area (paths 2 and 3). Two of the other paths traverse at least two areas (paths 1 and 4), and one crosses all three areas (path 5).

The spring test session (Figure 48) illustrates a drastically different configuration of high-probability paths. All seven paths either begin or terminate in area 1 with four paths enclosed within the area (paths 1, 2, 3, and 6). These results signify a much more constricted sphere of pedestrian movement relative to the baseline session, in which five paths traverse at least two areas.

The distribution of paths for the summer baseline period is illustrated in Figure 49. In contrast to the other seasons, three paths (paths 5, 6, and 7) begin and terminate within area 3. Three of the remaining paths

Fig. 47. Site D/Spring Baseline High Probability Paths

Fig. 48. Site D/Spring Test High Probability Paths



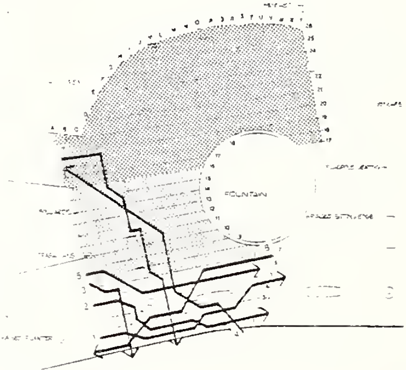
PATH
COORDINATES

1.	Q5	—	A7
2.	A5	→	03
3.	A1	—	N1
4	Q6	—	A14
5	A6	→	J26
6	A8	—	O21
7	K25	—	X18

KEY

- ☐ AREA 1
- ☐ AREA 2
- ▨ AREA 3

SPRING BASELINE



PATH
COORDINATES

1	A2	—	P4
2.	A5	—	N1
3.	A7	—	C1
4	M1	→	A17
5.	A8	—	C5
6.	Q6	—	A1
7	A17	→	G1

KEY

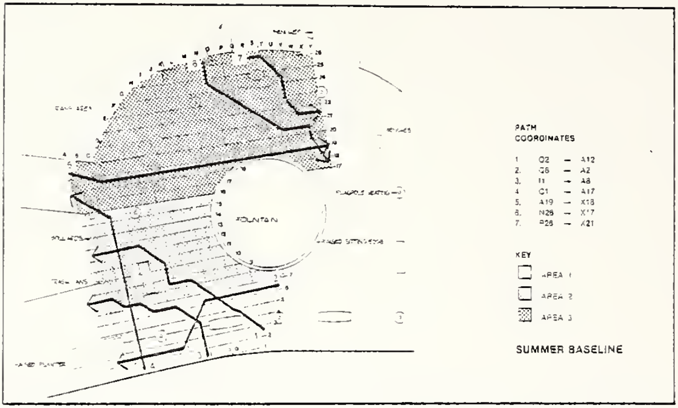
- ☐ AREA 1
- ☐ AREA 2
- ▨ AREA 3

SPRING TEST

STUDY SITE D
FILMING AREA · 4 3RD

Fig. 49. Site D/Summer Baseline High Probability Paths

Fig. 50. Site D/Summer Test High Probability Paths



PATH COORDINATES

1	O2	—	A12
2.	G6	—	A2
3.	I1	→	A8
4	C1	—	A17
5.	A19	—	X18
6.	N26	—	X17
7.	P26	—	X21

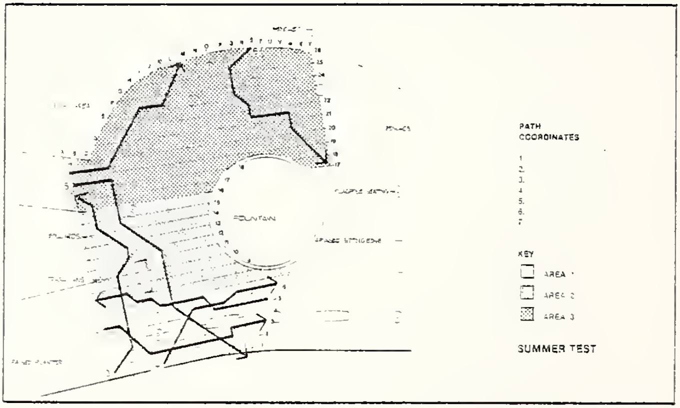
KEY

☐ AREA 1

☐ AREA 2

▨ AREA 3

SUMMER BASELINE



PATH COORDINATES

1
2.
3.
4
5.
6.
7

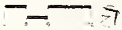
KEY

☐ AREA 1

☐ AREA 2

▨ AREA 3

SUMMER TEST



STUDY SITE D
RUNNING AREA - 4 GRID

(paths 1, 3, and 4) traverse at least two areas. Of the four paths originating in area 1, only one path (2) terminates there.

The summer test session (Figure 50) portrays a pattern which is similar in many respects to the baseline session. Three paths also begin within area 3, two exiting in the area (paths 6 and 7) and one terminating in area 1 (path 5). Three paths cross at least two areas, while the remaining two paths are enclosed totally within area 1. For both summer sessions the distribution of paths is more random and diffuse compared to the other sessions.

Velocity, Density, and Behavior.

The analysis of variance of pedestrian velocity yields a significant difference for season and session. Pedestrian speed during winter (3.6 ft/sec, 1.1 m/sec) is significantly greater than spring (3.1 ft/sec, 0.9 m/sec) and summer (2.9 ft/sec, 0.9 m/sec). Velocity during test sessions across seasons is significantly greater for test periods (3.5 ft/sec, 1.1 m/sec) than for baseline periods (2.9 ft/sec, 0.9 m/sec) (see Table 14).

Analysis of variance of pedestrian densities yields two significant effects: the summer season has significantly more individuals per frame (18 people/frame) than spring (6.3 people/frame) or winter (4.4 people/frame), and the baseline period has more individuals than the test

Table 14

Analysis of Variance of Velocity (Site D)

Source of Variance	Sum of Squares	df	Mean Squares	F Ratio
Season	59.281	2/180	29.641	12.611**
Session	18.218	1/180	18.218	9.208**
Season by Session	23.208	2/180	11.604	4.218

**$p \leq .01$

sessions (see Table 15).

The only significant difference for the behavioral data (see Table 16) is the number and duration of people sitting within the space. For the summer session there were significantly more people sitting in the space for a longer period of time than for the other two seasons. No significant differences are found in the platooning data.

Density Distribution.

Figure 51 exhibits the winter baseline density distribution. The distinguishing feature is that Area 1 (i.e , a space located adjacent to the main thoroughfare and bounded by the fountain) shows the highest density (1 square--3-4 people/square and 11 squares--2 people/square). Area 2 (i.e., the space adjacent to the fountain) displays moderate densities per square. Area 3 (i.e., the space opening into several pathways) has only one person in the entire space. The winter test sessions shows an analogous distribution (see Figure 52). Area 1 exhibits the highest density (9 squares--2 people/frame). Area 2 exhibits very low densities and Area 3 no pedestrians whatsoever.

Figure 53 displays the spring baseline session. The distribution of pedestrians is quite diffuse throughout the map grid. Area 1 exhibits the highest density (10 squares--2 people/square). Area 3 is the space with the next highest density (3 squares--2 people/frame), and Area 2 has the

Table 15

Analysis of Variance of Density (Site D)

Source of Variance	Sum of Squares	df	Mean Squares	F Ratio
Season	98.384	2/234	48/142	32.618**
Session	11.621	1/234	11.621	6.681**
Season by Session	28.695	2/234	14.347	10.321

$^{**}p \leq .01$

Table 16

Behavioral Analysis (Site D)

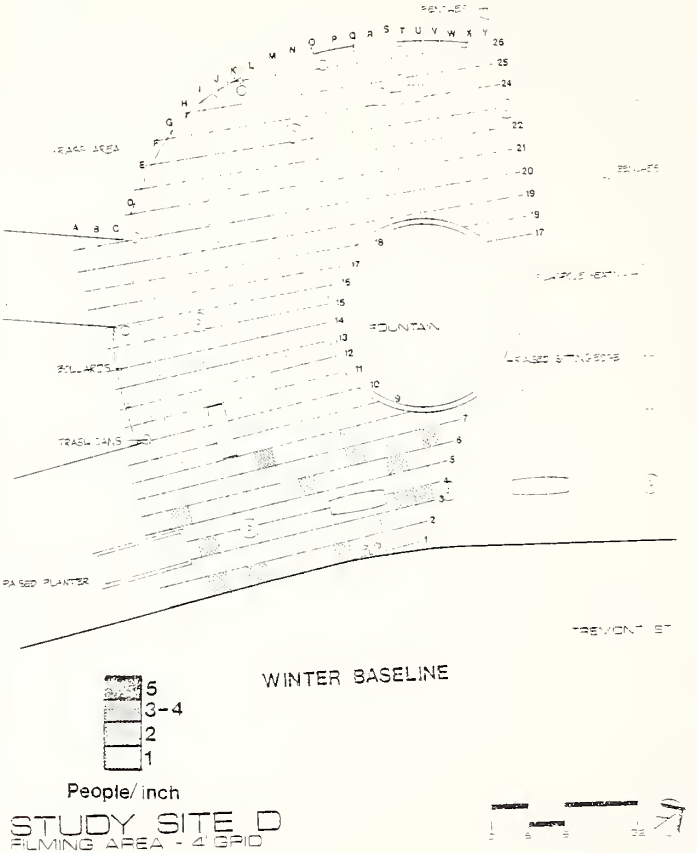
	Winter		Spring		Summer	
	Baseline	Test	Baseline	Test	Baseline	Test
Average number of pedestrians	4.03	4.88	9.75	2.93	18.65	13.55
Highest count	7	8	11	6	16	12
Lowest count	0	0	1	0	1	1
Average walking speed (ft/sec)	3.51	3.71	2.71	3.41	2.61	3.28
Number standing alone	4	3	3	4	2	5
Average time (sec)	12	18	12	8.5	16	24

Table 16 (continued)

Behavioral Analysis (Site D)

	Winter		Spring		Summer	
	Baseline	Test	Baseline	Test	Baseline	Test
Number standing groups	1	2	9	3	6	4
Average time (sec)	43	28	17	6.5	55	28
Number sitting	1	0	7	0	6	5
Average time (sec)	841	---	86	---	112	228
Total number platoons	34	52	72	23	83	90
2 people	28	45	51	19	66	70
3 people	5	6	11	4	11	12
4 people	1	1	9	0	5	8
5 people	0	0	1	0	0	0

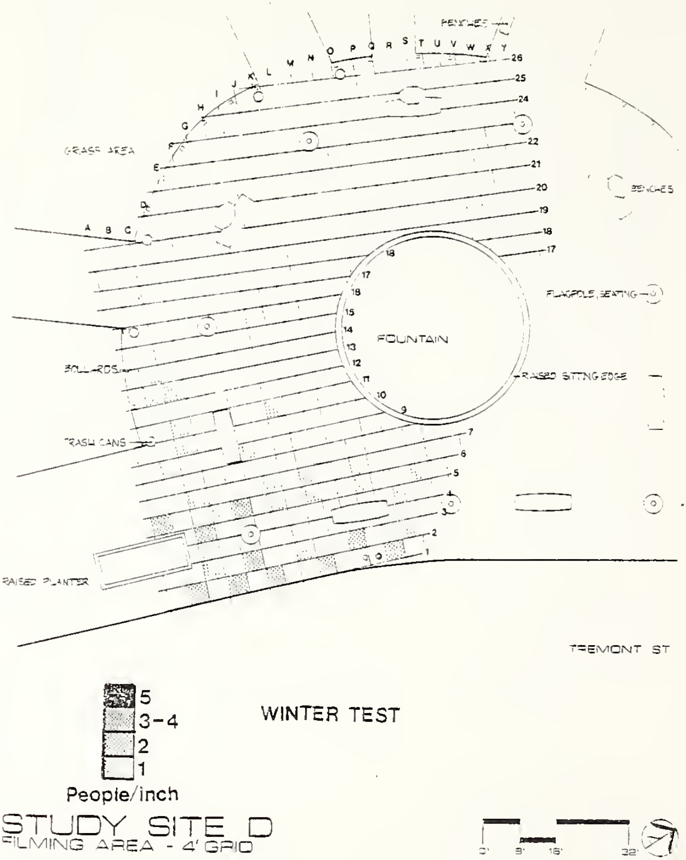
Fig. 51. Site D/Winter Baseline Density Distribution



WINTER BASELINE

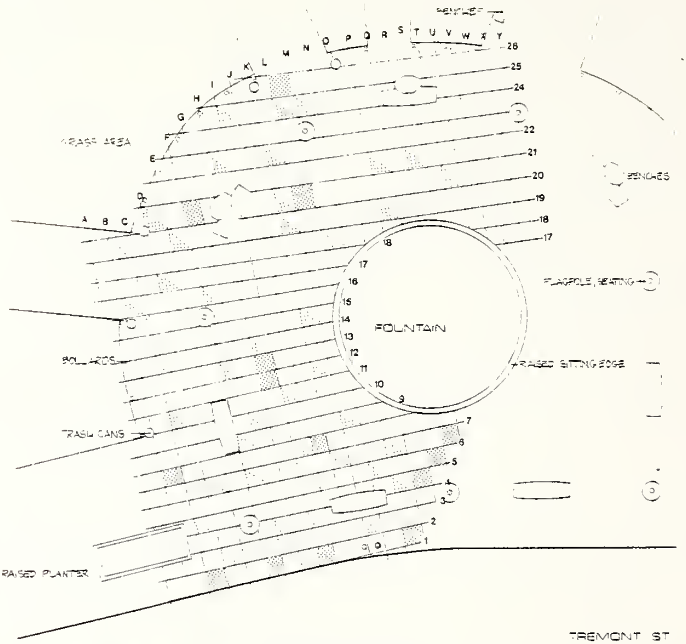
STUDY SITE D
FILMING AREA - 4' GRID

Fig. 52. Site D/Winter Test Density Distribution



STUDY SITE D
FILMING AREA - 4' GRID

Fig. 53. Site D/Spring Baseline Density Distribution



SPRING BASELINE

▩ 5
▦ 3-4
▨ 2
☐ 1

People/inch

STUDY SITE D
FILMING AREA - 4' GRID

0' 8' 16' 32'

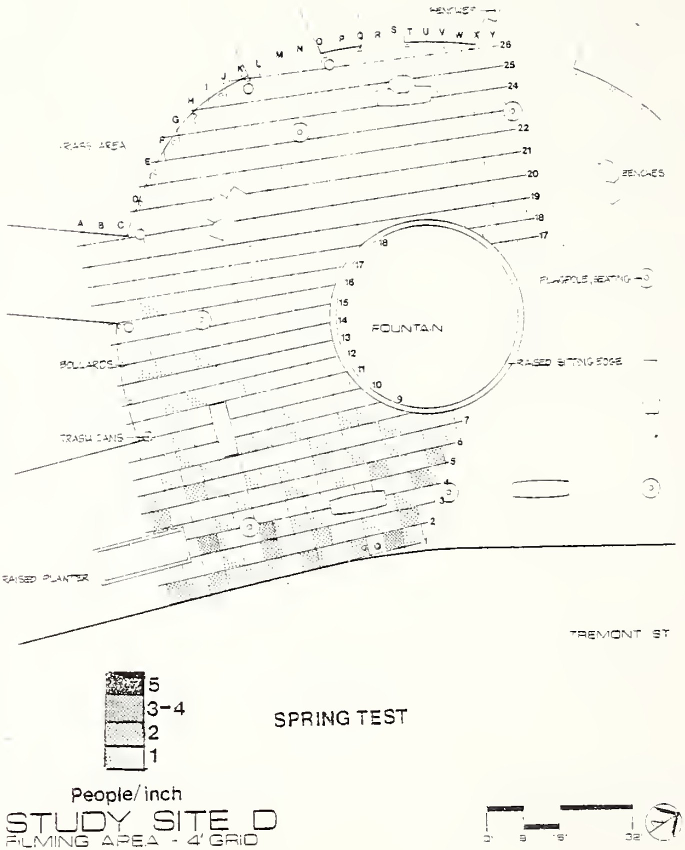
least number of pedestrians (2 squares--2 people/frame). Figure 54 exhibits the spring test session. In contrast to the baseline period, almost the entire density is located in Area 1 (3 squares--3-4 people/square and 10 squares--2 people/square). Area 2 shows a very light density and Area 3 no pedestrians whatsoever. These densities in Areas 2 and 3 contrast sharply with those during the baseline period.

Figure 55 displays the summer baseline session. The distribution pattern is extremely diffuse. Area 1 has the highest density (17 squares--2 people/frame). Area 3 has the next highest density (5 squares--2 people/frame), and Area 2 the lowest density. The summer test session shows a very similar pattern (Figure 56). Area 1 shows the highest density (17 squares--2 people/square). However, in this session Area 2 displays the second highest density (4 squares--2 people/square) and Area 3 the lowest density.

Wind Contour Maps and the Path Model

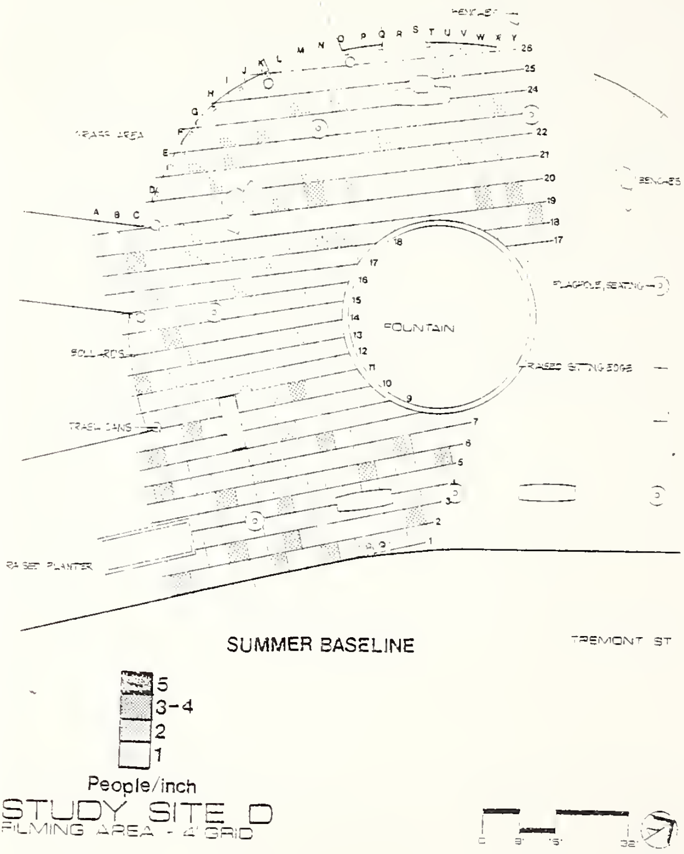
The preceding analyses of pedestrian movement for test and baseline days used the following operationalized definitions of wind speed: (1) a baseline day was defined as one in which the ambient wind speed measured at Logan Airport was less than or equal to 10 mph (4.5 m/s); and a test day was defined as one in which the ambient wind speed measured at Logan was greater than or equal to 20 mph

Fig. 54. Site D/Spring Test Density Distribution



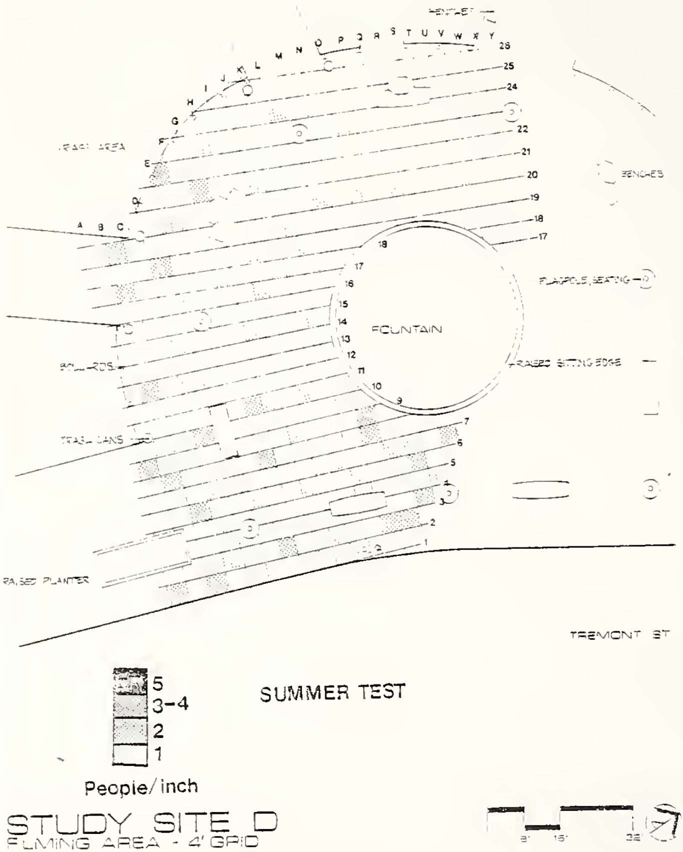
STUDY SITE D
FILMING AREA - 4' GRID

Fig. 55. Site D/Summer Baseline Density Distribution



STUDY SITE D
FILMING AREA - 4' GRID

Fig. 56. Site D/Summer Test Density Distribution



STUDY SITE D

FILMING AREA - 4' GRID

(9.1 m/s). Nonetheless, an effective analysis of wind conditions will also identify anticipated wind behavior throughout all parts of the study site. In order to do this it is necessary to incorporate data about prevailing wind conditions and patterns around tall buildings. Although it is certain that almost any area around a high-rise building can be uncomfortably windy when the wind is blowing from a particular direction, the existence of the prevailing wind patterns guarantees that certain portions of a site will be windy more frequently than other areas. As a result it is possible to more accurately identify the windier and calmer areas of a high-rise site

The prevailing wind pattern around a high-rise building can be most easily described through a wind-contour map (see Figure 57). The contour lines on such a map do not represent absolute wind speeds but rather degrees of calmness or turbulence. The number associated with each contour line (generally referred to as an "R" value) indicates the relative windiness of that area. Specifically, it indicates the percentage of the wind speed at the top of the building in question that is experienced on the ground at a given point. Thus, if the wind at the top of the building is 35 mph, an area bounded by 0.7 contour will experience winds of 24 mph (0.7 X 35 = 24). On a less windy day when speeds are only 25 mph at the top of the building, that same area would experience a wind of only 17 mph (0.7 X 25 = 17).

The theoretical formulation developed by Davenport (1968) allows one to calculate wind speeds at the top of a building from meteorological wind speeds at a nearby site. Coupled with this capability, the wind-contour map enables one to predict the wind speed at a given portion of the site when the direction and ground-level speed of the ambient wind is known.

These wind-contour values themselves can be generated in a number of different ways. If specific site conditions resemble the simple physical models used by Penwarden and Wise (1975), then a wind-contour map of a site can often be generated on the basis of their formulas. However, when the building design is unique it is necessary to rely on wind-tunnel tests to generate accurate information about wind patterns and contour values. The wind-contour maps used in this thesis are based on data gathered on site during the course of the study. These maps, consequently, represent the best theoretical extrapolations of limited data and their imprecise nature should be recognized.

Calculation of a wind contour proceeds as follows. Using Site A as an example, one can calculate that the velocity of wind at the top of the 500-foot building is 1 3 times greater than wind at an unobstructed ground-level station (meteorological wind). This value (generally referred to as "S") varies with building height. Wind-contour numbers indicate the percentage of building height winds experienced at the base of the building. Using appropriate values for the functions S and R, it is possible to determine the meteorological wind velocity required to produce a given velocity at the base of a building. This value is computed with the following format:

$$Va = Vb/R \times S/1.15$$

Where:

Va = meteorological wind speed

Vb = ground-level speed

R = percentage of building-height winds experienced at the base of the building (wind-contour number)

S = a value for unobstructed wind flow that varies with building height (See Appendix A)

1.15 = a correction factor for faster average daytime wind speeds.

Thus, if we wish to determine the meteorological wind speed (Va) required to produce a 20 mph velocity on a site (Vb) (where $R = 0.7$ and $S = 1.3$):

$Va = 20/(.07)(1.3)/1.15$

$Va = 20/.091/1.15$

$Va = 22/1.15$

$Va = 19.$

The answer, 19, tells us that on a day when meteorological winds average 19 mph, winds will be 20 mph in areas bounded by the 0.7 contour during peak-use conditions.

For the behavioral maps which follow (Figures 57-62), the appropriate wind contour patterns calculated from the above formula have been superimposed on the highest probability path distributions for selected sessions. Therefore, these figures present the simultaneous interaction of two theoretical models: (1) the wind contours which provide predictions of wind speed at particular areas in the map; and (2) the path model which provides the distribution of highest probability paths for the session in question.

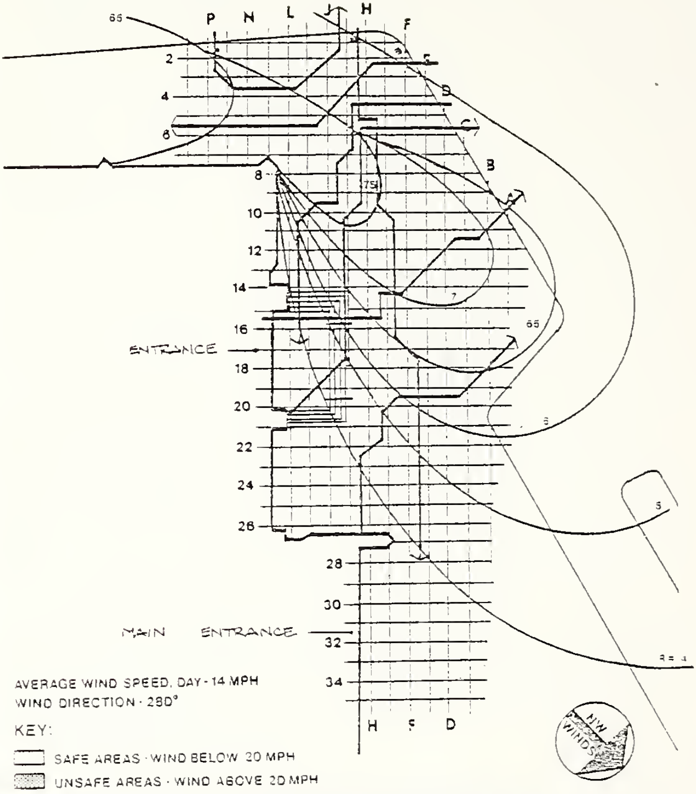
Path Pattern and Wind Contours for Site A--500-Foot Office Building.

Figure 57 displays the grid map for the 500-foot (152-meter) office building. In this grid map (and the ones that follow), the three areas have not been shaded in. In these maps a shaded area signifies an unsafe area where the wind speed has been calculated to be greater than 20 mph. For purposes of consistency the three areas will again be defined. Area 1 defines a walkway bounded by the corner of the office building and a major thoroughfare. This area is bounded by map coordinates one through eight. Area 2 designates the space of the building and a major thoroughfare. It is bounded by map coordinates eight through twenty-one. Area 3 represents the space adjacent to the lobby entrance of the building; it is bounded by map coordinates twenty-one and thirty-four.

The R values (e.g., percentage of building height

Fig. 57. Site A/Winter Baseline Path Pattern and Wind Contours

WINTER BASELINE



PATH PATTERN AND WIND CONTOURS - DAY 2

STUDY SITE A
PLAYING AREA - 5' GRID

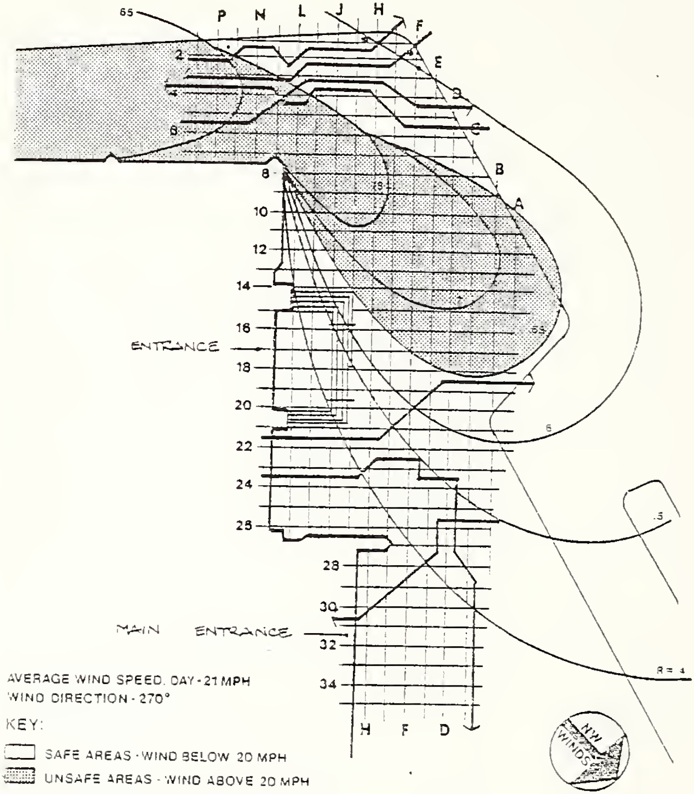
winds experienced at the base of the building) are given as follows: R = .4, R = .65, R = .7, R = .75. In this session (winter/test), the average wind speed was 21 mph. Using the wind contour model, all contours are calculated to be below twenty miles per hour and therefore safe for pedestrian usage.

Figure 57 displays the plotted paths for the seven high probability paths for the winter baseline period. It will be noted that three of the high-probability paths (1, 2, and 3) are either entrance or exit paths to the office building. One path (path 4) traverses all three areas, exiting at area 2. The distinguishing feature of the distribution of these paths is that five of the seven paths traverse area 2 in some manner. Hence the space adjacent to the building entrance was utilized most frequently by pedestrians during this session.

Figure 58 displays the wind contours and pedestrian paths for the winter test session. The R values are: R = .4, R = .65, R = .7, and R = .75. In this session, the average wind speed was 21 mph. Using the formula Va = Vb/R X S/1.15, it is calculated that for R = .65, R = .7, and R = .75, the ground level wind speeds are above 20 mph, making these areas unsafe for pedestrian movement. In Figure 58 these areas are shaded (the wind contours are shaded). For the unshaded areas, the ground level wind speed is calculated to be less than 20 mph.

Fig. 58. Site A/Winter Test Path Pattern and Wind Contour

WINTER TEST



AVERAGE WIND SPEED, DAY - 21 MPH
WIND DIRECTION - 270°

KEY:

☐ SAFE AREAS - WIND BELOW 20 MPH
▨ UNSAFE AREAS - WIND ABOVE 20 MPH

PATH PATTERN AND WIND CONTOURS - DAY 4

STUDY SITE A
FILMING AREA - 5' GRID

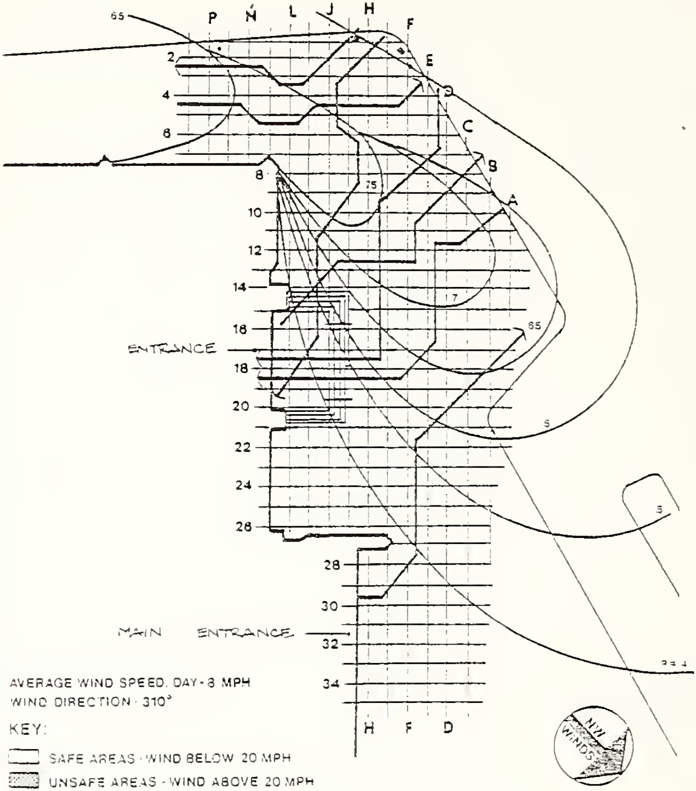
0 20 40

It will be immediately noted from Figure 58 that the four highest probability paths begin or terminate within the shaded area of dangerous wind speeds. Boths paths 1 and 2 begin in areas of moderate wind speed (less than 20 mph) and proceed to enter shaded wind contours of high turbulence (R = .75). On the other hand, paths 3 and 4 begin in the shaded wind contours (R = .75). Therefore, the four most frequently used paths are beginning or terminating in the areas with the highest wind speeds (areas of unsafe pedestrian movement). Paths 5, 6, and 7 remain for their entire distance in unshaded wind contour areas of more moderate speed. It should be noted that no paths whatsoever traverse the building's entrance. This area (most of area 2) is almost completely shaded and therefore unsafe.

In Figure 59 the wind contours and pedestrian paths are displayed. The R values are as follows: R = .4, R = .65, R = .7, and R = .75. For this session the average wind speed was 8 mph. For all wind contours the calculated ground level wind speed was in the safe region. This is reflected in the distribution of high-probability paths. It will be noted that four paths either commence (path 6) or exit (paths 3, 4, and 5) at the building entrance. Two paths are encompassed within area 1 (paths 1 and 2) and one path begins in area 3 and exits in area 2 (path 7). Three paths traverse at least two areas, and five paths

Fig. 59. Site A/Summer Baseline Path Pattern and Wind Contours

SUMMER BASELINE



AVERAGE WIND SPEED. DAY - 8 MPH
WIND DIRECTION · 310°

KEY:

▭ SAFE AREAS · WIND BELOW 20 MPH
▨ UNSAFE AREAS - WIND ABOVE 20 MPH

PATH PATTERN AND WIND CONTOURS - DAY 1

STUDY SITE A
PLAYING AREA - 5' GRID

cross area 2 to some degree. In general, the distributions of paths are very diverse.

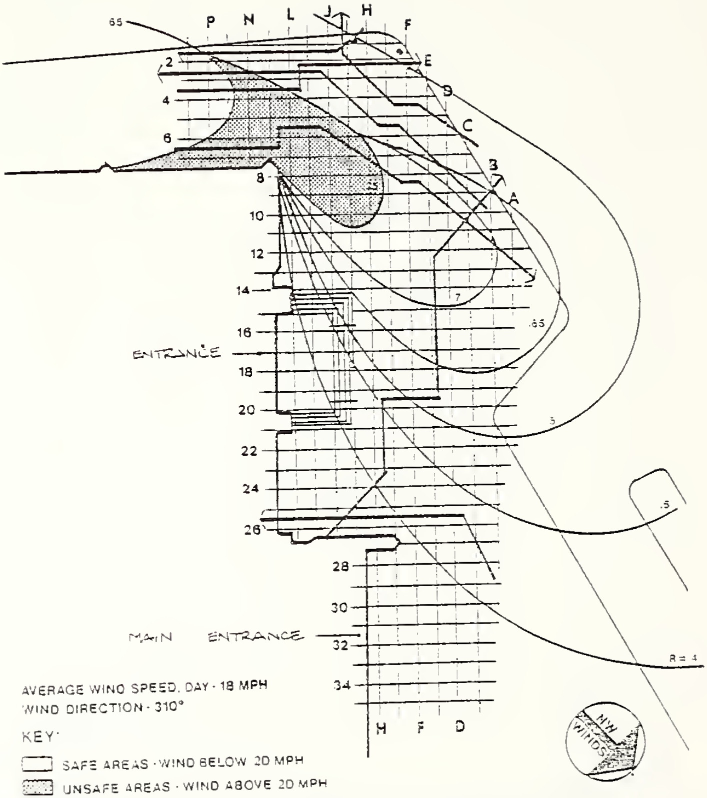
In Figure 60, the high-probability paths and wind contours are presented. The R values are as follows: R = .4, R = .5, R = .6, R = .7, and R = .75. The wind speed for this session was 18 mph. For this session the R = .75 wind contour is the only one where the ground level speed is greater than 20 mph. Although none of the seven high-probability paths begin or exit at the building entrance, three paths are completely bound in the area of greatest wind turbulence. Two paths begin (paths 1 and 2) and one path terminates (path 5) in the R = .75 wind contour. Whereas in the baseline period five paths cross area 2, in the test session, five paths traverse area 1, the area of greatest wind speed. Only three paths cross two areas in the test session, compared to the five crossovers in the baseline period. Compared to the test session, the path configuration on the baseline day is much less diffuse.

Site B--600-Foot Office Building.

Figure 61 displays the grid map for the 600-foot office building. This grid is divided into the following three areas: area 1 is a space adjacent to the main entrance of the building; area 2 is a space adjacent to the secondary entrance and extends to a pathway; and area 3 is bounded by a series of stores and a fountain within the

Fig. 60. Site A/Summer Test Path Pattern and Wind Contours

SUMMER TEST



AVERAGE WIND SPEED, DAY - 18 MPH
WIND DIRECTION - 310°

KEY:

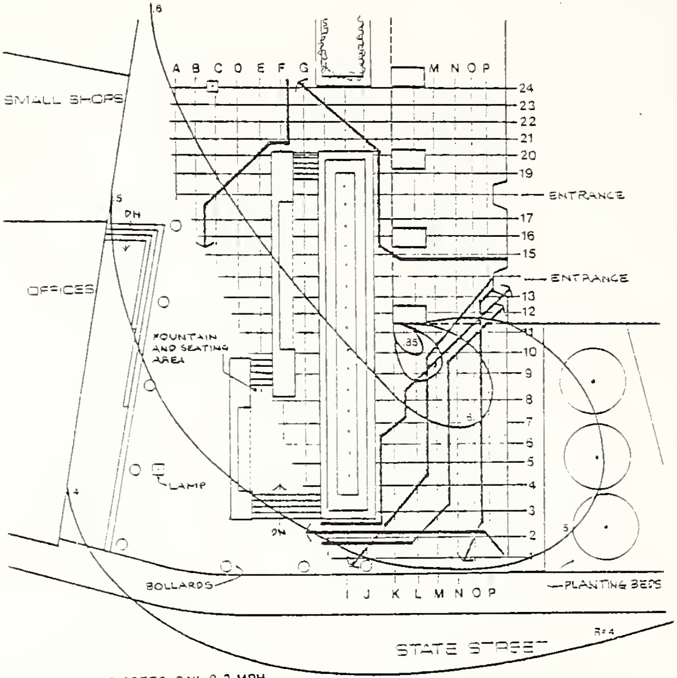
☐ SAFE AREAS - WIND BELOW 20 MPH
▨ UNSAFE AREAS - WIND ABOVE 20 MPH

PATH PATTERN AND WIND CONTOURS - DAY 3

STUDY SITE A
FILMING AREA - 5' GRID

Fig. 61. Site B/Summer Baseline Path Pattern and Wind Contours

SUMMER BASELINE



AVERAGE WIND SPEED DAY - 8.2 MPH
WIND DIRECTION · 310°

KEY:

▭ SAFE AREAS · WIND BELOW 20 MPH
▨ UNSAFE AREAS · WIND ABOVE 20 MPH

PATH PATTERN AND WIND CONTOURS - DAY 1

STUDY SITE 8
FILMING AREA - 5' GRID

space.

For this site the R values are given as follows: R = .4, R = .5, R = .6, and R = .85. On this day the average wind speed was 8.2 mph. All contour areas were designated in the safe region. This is reflected in the distribution of high-probability paths. Five high-probability paths have their endpoints at the principal entrance. Three paths commence and two exit at this point.

In Figure 62, the high probability and wind contour maps are presented for the winter test period. The R values are as follows: R = .4, R = .5, R = .6, and R = .85. On this day the ambient speed was 21 mph. For this session the R = .6 and R = .85 wind contours were the ones where the ground speed is unsafe. Interestingly, five of the high probability paths are contained in this area. Four paths have endpoints at the building's entrance (paths 1 and 2) and two terminate at the entrance (paths 3 and 4). Path seven is also contained within the unsafe area.

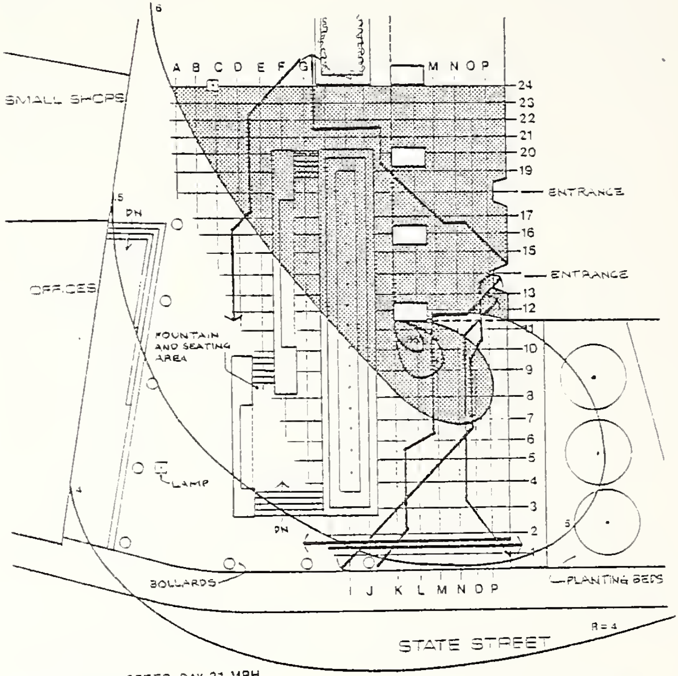
Questionnaire Data.

The questionnaire was administered to two populations under six different conditions. The number of occurrences for each sample group is listed in Table 17.

The job characteristics of the respondents reflects a typical downtown urban population. Approximately 52 percent of the questionnaire subjects were clerical workers.

Fig. 62. Site B/Winter Test Path Pattern and Wind Contours

WINTER TEST



AVERAGE WIND SPEED. DAY-21 MPH
WIND DIRECTION · 270°

KEY:

☐ SAFE AREAS - WIND BELOW 20 MPH
▨ UNSAFE AREAS - WIND ABOVE 20 MPH

PATH PATTERN AND WIND CONTOURS - DAY 4

STUDY SITE B
FILMING AREA - 5' GRID

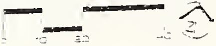


Table 17

Questionnaire Population for Site C and Site A

City Hall Plaza (Site C)

	winter	spring	summer
Test	26	29	30
Baseline	32	31	28
			176

500-ft Office Building (Site A)

	winter	spring	summer
Test	32	31	32
Baseline	28	32	29
			184

Interestingly, the percentage of clerical workers was significantly higher at Site A (64%) than Site C (40%). For the entire survey 35 percent of the population were managerial/professional. The percentage of professional workers at Site C (49%) was significantly higher than at Site A (23%). Finally, the overall percentage of technical workers was 8 percent (Site A = 9%, Site C = 7%).

Overall, the survey population had a significantly greater number of females than males. Fifty-eight percent of those who responded were females and 40% were males. For City Hall Plaza (Site C) the percentages were approximately equal (males = 47%, females = 55%), whereas for the 500-foot office building (Site A) there were twice as many females as males (males = 34%, females = 64%). The percentage breakdown for the sexes probably reflects the fact that the percentage of professional workers was much higher at Site C.

Finally, respondents were asked to name the mode of transportation they utilized in getting to work everyday. The breakdown of the results is as follows: (1) automobile--Site A = 21%, Site C = 22%; (2) public transportation--Site A = 72%, Site C = 61%; and (3) walking--Site A = 2%, Site C = 11%. Overall the vast majority of people utilized public transportation at both sites (67%).

Semantic Differentials.

The first part of the questionnaire presented four pictures each with five semantic differentials (only the calm-windy differential scale was common to all pictures). The purpose of this section of the survey was to measure the meaning of different scenes. Two of the pictures (pictures A and C) were in the immediate vicinity of the corresponding lettered test sites. Analysis of variance was applied to each of the semantic differentials for all of the pictures. The sources of variance were the following: population (population A and population C); season (winter, spring, and summer), and test condition (test versus baseline sessions).

Picture A. First of all, this picture was rated as being more windy (4.2) by population A than population C (3.89) (F = 4.5, df = 2/262, p = .04). This picture was also rated as more windy during the spring (4.19) and winter (4.13) sessions than the summer period (F = 4.0, df = 1/262, p = .02). In addition this picture was rated quietest during summer (2.28) and noisiest during the spring (3.47) (F = 4.5, df = 2/262, p = .01). Population A also rated this picture as being noisier during windy test conditions (3.41) than baseline conditions (2.73), while there was no difference for population C (F = 4.5, df = 1/262, p = .03). For the exposure rating the scene was rated more exposed during the test sessions (F = 9.4, df = 1/262, p = .002). Moreover, population A rated this picture to be most exposed during the summer and least during the spring, while population C rated it as being more exposed during summer and least during the spring (F = 4.4, df = 2/262, p = .01). For the "hot/cold" differential, the picture was rated colder during test sessions (F = 5.5, df = 1/262, p = .02). Finally for the comfortable/uncomfortable differential there were two significant differences. This picture was rated significantly more uncomfortable during test periods (F = 6.1, df = 1/262, p = .02). Also, population A rated this scene as more uncomfortable during the winter (3.89) and spring (3.81), whereas population C rated it more uncomfortable during the summer (3.86) than the other two seasons (F = 6.4, df = 2/262, p = .05).

Picture B. For Site B population C rated this picture significantly more windy (4.19) than population A (3.46) (F = 20.2, df = 1/261, p = .001). There is also a significant interaction between population and session for the windiness scale. Population C rated this scene more windy for test sessions (4.26) than for baseline sessions; and population A rated this scene as more windy during test sessions (3.66) as compared to baseline periods (3.24) (F = 4.4, df = 1/261, p = .03). For the hostility semantic scale, this picture was rated more hostile during test sessions (4.1) than for baseline periods (3.22) (F = 14.12, df = 1/261, p = .001). Respondents differed significantly on three sources of variance for the hot/cold scale. Population C (3.71) rated the scene colder than population A (3.32) (F = 5.94, df = 1/261, p = .01). In addition it was rated significantly colder (3.82) during baseline sessions than test periods (3.28) (F = 18.63, df = 1/261, p = .001). Finally, there was a significant effect for the location/session interaction. Picture B was rated coldest by population C during baseline periods (3.70) than during test sessions (3.56); while for test sessions there was no difference between populations A and C (F = 7.92, df = 2/261, p = .001). For the safe/dangerous scale, the picture was rated more dangerous on test (3.21) than baseline (2.89) sessions (F = 5.59, df = 1/261, p = .01). Likewise, the scene was rated more chaotic on test days (2.82) than for baseline periods (2.31) (F = 22.56, df = 1/261, p = .001). Finally, the respondents in population A rated this picture as being more chaotic during test periods, while population C rated the scene least chaotic during baseline periods (F = 5.67, df = 1/261, p = .01).

Picture C. For Picture C three of the semantic scales--calm/windy, good/bad, and comfortable/uncomfortable--showed no significant differences for any source of variance. However, for the inviting/uninviting scale, population C (2.21) rated the picture more inviting than population A (2.98) (F = 4.39, df = 1/261, p = .03). There were two significant effects calculated for the safe/dangerous scale. Overall this picture was rated less safe during test days as compared to baseline periods (F = 8.87, df = 1/262, p = .003). An analysis of the session/location interaction shows that population C rated the scene less safe during test sessions (2.82) as compared to baseline periods (2.15), whereas population A scored the picture about equally for both sessions (F = 4.41, df = 1/262, p = .03).

Picture D. For Picture D there were no significant differences for the wind/calm semantic scale. Only one semantic differential provided a significant difference between the two populations. Population A rated this scene to be more exposed for baseline (4.44) days as compared to test session (3.88), while for population C there were no significant differences between the two sessions (F = 5.30, df = 1/259, p = .02). This picture was also rated more exposed during baseline sessions (4.11) than test sessions (3.79) (F = 28.10, df = 1/259, p = .001). This picture was also rated more exposed during the winter (4.10) and spring (3.96) and the least exposed on windy sessions during the summer and winter (F = 16.46, df = 2/259, p = .001). In addition this picture was rated more ordered during summer (2.52) as compared to spring (2.68) and winter (3.11) (F = 2.46, df = 2/259, p = .02). Picture D was also calculated to show a significant difference between date and session for the inviting/uninviting scale: Specifically, while there was no difference during the two winter sessions, the spring baseline session (2.81) was rated more inviting than during the spring test session (2.92), and the baseline summer session (2.72) was rated less inviting than during the summer test session (2.62) (F = 3.97, df = 2/259, p = .02). Finally, for the bright/dull scale, the picture was rated brightest for the summer test session (2.42) and the dullest during the spring test session (2.73) and the summer baseline sessions (2.65) (F = 5.95, df = 2/259, p = .003). Means and standard deviations for the scales are listed in Table 18.

The Attitude Survey.

In the second part of the questionnaire, respondents were presented with 16 attitudinal statements concerning general features of the wind environment. They were asked to evaluate each item on a 5-point scale from "strongly agree" to "strongly disagree". Analysis of variance was applied to each item. The sources of variance for all analyses were: (1) population (A and C), (2) season (winter, spring, and summer), and (3) test condition (baseline and test). Table 19 provides the means and standard deviations for each item.

First of all six questions showed no significant effects. These items are the following:

Item 2--"I would rather travel underground...on windy days."

Table 18

Means and Standard Deviations for Each of the Five Semantic Differential Scales for the Four Pictures

Picture C (City Hall Plaza)

Scale	Mean	S.D.
Calm-Windy	3.68	1.30
Inviting-Uninviting	2.85	1.33
Comfortable-Uncomfortable	2.81	1.14
Safe-Dangerous	2.61	1.17
Good-Bad	2.58	.98

Picture D (Boston Common)

Scale	Mean	S.D.
Calm-Windy	3.31	1.32
Inviting-Uninviting	2.96	1.31
Protected-Exposed	3.93	1.16
Ordered-Chaotic	2.97	1.16
Dull-Bright	2.67	1.31

Picture A (500-Foot Office Building)

Scale	Mean	S.D.
Calm-Windy	4.05	1.26
Hot-Cold	3.71	1.08
Comfortable-Uncomfortable	3.70	1.14
Protected-Exposed	3.92	1.17
Quiet-Noisy	3.13	1.47

Table 18 (continued)

Means and Standard Deviations for Each of the Five Semantic Differential Scales for the Four Pictures

Picture B (600-Foot Office Building)

Scale	Mean	S.D.
Calm-Windy	3.82	1.35
Hot-Cold	3.42	1.01
Safe-Dangerous	2.86	1.12
Ordered-Chaotic	2.45	1.23
Friendly-Hostile	3.01	1.08

Please Note: The directionality of some of the scales has been inverted so that comparisons across the pictures can be made with minimal confusion. In most cases above, the ordering has been placed in a positive (value of 1) to negative (value of 5) connotation. In all cases a "neutral" response is equivalent to a rating of 3.

Table 19

Means and Standard Deviations for Attitude Survey Items

		Mean Agreement Rating	Standard Deviation
1.	I find the wind conditions outside this ...building to be usually rejuvenating.	3.44	1.23
2.	I would rather travel underground or take an alternate route to and from work on windy days.	2.50	1.19
3.	Unpleasant wind conditions occur so infrequently that they rarely bother me.	3.54	1.13
4.	If I have plans to browse or shop during my lunchbreak, I will postpone them on windy days.	3.03	1.25
5.	Windy days do not interfere with my plans in choosing a restaurant during lunchtime.	2.79	1.14
6.	When there are high winds, I find that I try to avoid them by various means.	2.33	1.12
7.	When I have errands to run during lunchtime, strong winds do not present an obstacle.	3.05	1.24
8.	In general, I feel that the winds occurring outside my office building are invigorating and refreshing.	3.55	1.19

Table 19 (continued)

Means and Standard Deviations for Attitude Survey Items

		Mean Agreement Rating	Standard Deviation
9.	The dust and debris which gusty winds "kick up" interfere with my ability to maneuver outside my office building.	2.56	1.12
10.	Usually I do not notice the wind at all.	3.96	1.02
11.	When wind conditions are troublesome, I occasionally experience difficulty in walking near my office building.	2.15	1.10
12.	Wind conditions bother me only when it is cold or rainy.	2.85	1.71
13.	After entering my office building on a windy, gusty day, I feel disorganized and ruffled.	2.45	1.15
14.	Generally, I find the wind conditions outside my office building to be offensive.	2.62	1.13
15.	The wind conditions that I experience in traveling to my office influence my attitude towards my work.	3.48	1.09
16.	There are times when I enjoy going outside on windy days.	2.77	1.10

Item 5--"Windy days do not interfere with my plans... during lunchtime."

Item 6--"When there are high winds...I try to avoid them by various means."

Item 9--"The dust and debris interfere with my ability to maneuver..."

Item 11--"When wind conditions are troublesome, I occasionally experience difficulty. ."

Item 12--"Wind conditions bother me only when it is cold or rainy."

For statement 1 there were two significant two-way interactions--date and population, and date and session. During the winter respondents in population A (2.82) agreed with statement 1 significantly more than the other groups and were somewhat more neutral during spring (3.12) and summer (3.22) (F = 3.57, df = 2/339, p = .02). For the data-session interaction, subjects significantly disagreed with the statement during the winter baseline sessions (3.52) and test sessions (3.34) (F = 3.41, df = 2/339, p = .03).

Statement 3 ("Unpleasant wind conditions rarely bother me.") shows one significant difference--the two-way interaction between date and session. Winter test (2.21) and baseline (2.52) sessions provided the most agreement with this question (F = 4.66, df = 2/339. p = .01).

For statement 4 ("I will postpone shopping on windy days.") there were two significant main effects--date and session. Respondents significantly agreed with statement 4 during the winter sessions (2.82) as compared to summer (3.12) and spring (3.24) sessions (F = 4.07, df = 2/339, p = .01). On test days (2.71) respondents agreed with this statement as compared with baseline periods (2.82) (F = 5.90, df = 1/339, p = .01).

Statement 7 ("Strong winds do not present an obstacle for running errands.") produced one significant effect (season of the year). Respondents significantly agreed with this statement during summer (2.82) as compared to spring (3.12) and winter (3.02) (F = 4.15, df = 2/343, p = .01).

Statement 8 ("I feel that the winds occurring outside my office are invigorating.") produced two significant effects--season and a two-way interaction between date and session. Respondents disagreed with this statement more during baseline sessions (3.63) as compared with test sessions (3.52) (F = 4.63, df = 1/343, p = .03). For the interaction, winter baseline sessions (3.93) were significantly greater than spring baseline (3.73) and summer test (3.68) periods. Winter test (3.26), spring test (3.34), and summer baseline (3.34) periods were significantly less than the other sessions (F = 5.55, df = 2/343, p = .004).

Statement 10 ("Usually I do not notice the wind at all.") produced the strongest disagreement of all the items.

For the test days respondents significantly disagreed with this item (4.21) as compared to baseline periods (3.82) (F = 10.63, df = 1/343, p = .001). Moreover, there was also a significant two-way interaction between date and session. The summer (4.32) and winter (4.28) sessions produced significant disagreement as compared to the other sessions (F = 13.89, df = 2/343, p = .001).

Statement 13 ("On windy days, I feel disorganized and ruffled.") produced one significant main effect (population) and one significant two-way interaction (date-population). Population A (2.12) tended to agree more with this item than population C (2.38) (F = 6.59, df = 1/346 p = .01). For the interaction the primary significant effect was that population A agreed with this item during the winter season than the other seasons (F = 3.87, df = 2/346, p = .02).

Statement 14 ("I find wind conditions outside my office building to be offensive.") produced two significant main effects (population and session). Respondents in population A (2.51) significantly agreed with this item compared to population C (2.71) (F = 3.38, df = 1/346, p = .03). For season, respondents agreed with this statement significantly more in winter (2.56) as compared with the other seasons (F = 5.53, df = 1/346, p = .03).

Statement 15 ("Wind conditions influence my attitude towards work.") produced one significant main effect (session) and two significant two-way interactions (season/population and season/session). During test sessions (3.63) respondents disagreed more with this item than baseline periods (3.42) (F = 11.14, df = 1/346. p = .001). During the summer and spring sessions respondents in population A disagreed with this item significantly more than those in population C during any season (F = 5.9, df = 2/346, p = .003). For the season/session interaction, the respondents in winter test sessions scored significantly more disagreement than the other periods (F = 3.06, df = 1/341, p = .02).

Statement 16 ("There are times when I enjoy going outside on windy days.") produced one significant main effect (session) and one significant interaction (population/session). Respondents agreed more with this statement during baseline periods (2.42) than test sessions (2.82) (F = 4.84, df = 1/347, p = .04). For the interaction, population C in test sessions agreed more with this statement than this population in baseline periods and more as compared with population A during either baseline or test sessions (F = 6.53, df = 1/347, p = .01).

Behavioral Responses.

This section of the questionnaire was utilized to assess three different aspects of the subject's outdoor behavior. Part 1 asked the respondents whether they would postpone running errands or going outside during the lunch hour because of the weather. Approximately 77% of the respondents stated yes to this question.

Part 2. In part 2 the subjects were asked to list the number of times each month that they engaged in a variety of different activities during lunch hour. Table 20 reports the means, the percentage that the activity was engaged in 5 or more times per month, the percentage the activity was deferred due to wind condition.

Analysis of variance was applied to this data using the same sources of variances as utilized in the analyses for the semantic differentials and the attitude items.

For the item "take a walk" there were two significant main effects (season and session). During the summer season respondents took more walks than the other two seasons (F = 3.8, df = 2/297, p = .02). Also respondents took more walks during baseline periods than test days (F = 5.1, df = 1/286, p = .02). For the "sit outside and relax" item, respondents scored significantly higher for summer than for the other seasons (F = 10.58, df = 2/286, p = .001).

For the item "eating lunch outdoors" there were several significant effects. Respondents in population C reported that they ate lunch outdoors more often than population A (F = 13.61, df = 1/286, p = .001). Population A reported that they ate lunch outdoors more frequently during summer sessions and least frequently than winter periods (F = 4.0, df = 2/286, p = .01). Finally, population C reported this

Table 20

Means, Percentages, and Percentages of Deferred Responses for Behavioral Categories

Behavioral Activity	Mean	Percentage of Activity 5 or more times per month	Overall, deferred due to Wind Conditions
Go outside for lunch	8.25	82%	19%
Take a walk	6.07	74%	22%
Sit outside	1.74	48%	16%
Eat lunch outdoors	1.72	30%	21%
Run personal errands	6.21	79%	8%
Go shopping	6.20	68%	7%
Go to bank	3.10	32%	3%

activity significantly more on baseline periods than test sessions (F = 5.77, df = 1/286, p = .01).

For the item "running personal errands" there were three significant effects. Respondents reported that they ran personal errands significantly more during baseline periods as compared to test sessions (F = 19.55, df = 1/300 p = .001). This activity was likewise reported significantly more in summer than the other seasons (F = 4.08, df = 2/300, p = .01). Finally, population C reported this activity significantly more in summer sessions as compared to spring and winter sessions; and population A reported more errands run during the winter as compared to other sessions (F = 2.71, df = 2/300, p = .02).

For "going to the bank" there were three significant main effects and one significant interaction (season/location). Respondents went to the bank significantly more during baseline periods as compared to test sessions (F = 20.35, df = 1/300, p = .001). This activity was reported more frequently in summer as compared to the other seasons (F = 5.16, df = 2/300, p = .006). For the final main effect, population C reported that they went to the bank more often compared to population A (F = 17.71, df = 1/300, p = .001). For the interaction, population C reported this activity significantly more during the summer than the other seasons (F = 2.2, df = 2/300, p = .05).

<u>Part 3</u>. For the final behavioral section, subjects

were asked whether or not they changed their routes to their offices during bad weather. Thirty-eight percent responded always, twenty percent sometimes, and forty-two percent never. For the respondents who do change their routes (58%) their alternative choices are presented in Table 21. These results are presented by site (A and C) and winter and summer.

Economic Data.

All receipt data obtained for the economic analysis were correlated with average wind speeds as recorded by the National Weather Service for the appropriate day. Data were collected from three locations at Site A; two shops at Site B; one location at Site C; and one location at Site D. The Pearson correlation coefficients are listed below in Table 22. Significant negative correlations were recorded only at the two locations at Site B. All other correlations were statistically significant.

Table 21

Percentage of Total Choice of Alternate Routes for Winter and Summer

Alternate Route	Building Site C winter	Building Site C summer	Building Site A winter	Building Site A summer
Provides Shade	5%	14%	3%	3%
Provides Sure Footing	17%	12%	28%	16%
Is protected from wind	32%	25%	37%	22%
Less pedestrian traffic	12%	1%	11%	6%
Is Sunny	5%	27%	6%	18%
Provides protection/rain	13%	8%	12%	7%
More pedestrian traffic	10%	6%	2%	7%
Less vehicular traffic	6%	5%	--	5%

Percentage of total choices of alternate routes for winter and summer for respondents who follow a different route when weather conditions are bad.

Table 22

Correlations for Consumer Data for Four Sites

Site A	Site B	Site C	Site D
Location			
1 .08	1 -.76*	1 -11	1 .08
2 .14	2 -.65*		
3 .17			

*p = .05

CHAPTER V

DISCUSSION

Site A--Sidewalk Adjacent to a 500-Foot Office Building.

In this study the fastest wind speeds were measured at this site. As has been argued, average wind speed conditions of 20 mph (9.1 m/sec) or over could endanger pedestrian safety. One pedestrian was actually blown over at this site on February 25, 1977 when the average wind speed was measured at 19.6 mph (8.9 m/sec). For elderly people the onset of dangerous wind speeds will occur at a lower average wind speed. Average wind speeds of 14 mph (6.4 m/sec) and over were observed to cause balance problems at this site, and wind-chill effects were clearly evident.

If the office building adjoining Site A had been designed to encourage casual pedestrian level activities, such as window shopping, it is evident that these conditions would frequently be unsuitable. This fact was dramatically illustrated by the pedestrian path analysis, which shows the effects of high wind speeds on pedestrian movement and path directionality.

Specifically, for both the summer and winter sessions (the spring to a lesser extent), the distribution of high-probability paths within this space differs significantly between the baseline and test sessions. For basline periods the distribution of paths is more random and diffuse compared to the test sessions. For the winter and summer baseline periods, 43 percent and 57 percent of the high-probability paths either begin or terminate at the building entrance. However, no paths whatsoever cross the building entrance during the test sessions for these respective seasons. Moreover, the effects of high wind speeds effectively makes area 2, which is adjacent to the entrance, unnegotiable for pedestrians.

Not only is the entrance underutilized during these sessions, but the percentage of paths which traverse area 2 is drastically reduced. Although 86 percent and 72 percent of all high-probability paths cross area 2 during the winter and summer baseline sessions respectively, only 14 percent (winter) and 42 percent (summer) traverse the same area for the corresponding test sessions. During the test session instead of negotiating paths toward the building, pedestrians shift their pattern movement to area 1, the major walkway bypassing the building in this space. This highly discernable shift of paths is significant, for the paths in area 1 allow the pedestrian to move in the space without passing the building entrance. In addition it provides the shortest possible distances for crossing this environment.

The configuration of paths during the test sessions is also more highly structured than during the baseline sessions. During the winter and summer test periods, 57 percent and 43 percent of all paths, respectively, are completely enclosed within area 1. Compared to the high degree of path crossovers in the baseline sessions, the high percentage of paths enclosed within area 1 signifies that the utilization of the space is drastically reduced during the high-wind speed conditions. Therefore, while the baseline sessions display a generally diffuse and random distribution of paths throughout the space, the test sessions are characterized by a more highly structured and less variable distribution of paths. In general, then, for these two seasons (and to a lesser extent, spring), the effects of high wind speeds completely change pedestrian utilization of the space by shifting the majority of high-probability paths from area 2 (baseline) to area 1 (test) and making paths toward the building highly unlikely.

The pedestrian velocity and density data for the investigations at this building yield significant differences between baseline and test sessions, which tend to confirm the path analysis. Pedestrian velocity during baseline sessions (2.7 ft/sec, 0.8 m/sec) is slower than velocities during test sessions (3.4 ft/sec, 1.1 m/sec). There is a significant velocity difference for season, with the average summer velocity significantly slower than the other seasons. Interestingly, the average baseline velocity is approximately equal to the average summer velocity, whereas the average test velocity is greater than any of the average seasonal velocities. Pedestrians, then, regardless of season, move faster in this space during high wind speed days.

The density analysis likewise confirms the differential characteristic of the baseline and test sessions. Baseline densities across seasons (3.3 people/frame) are greater than test sessions (2.1 people/frame). Again, there is a seasonal difference, with spring displaying a significantly greater density than other seasons. The analysis of pedestrian behavior yields no significant findings between sessions primarily because the frequency of behavior in this space is insignificant (at most several occurrences during any season). This finding is not surprising since this space is primarily a series of walkways without pedestrian conveniences.

The wind contour analysis also provides interesting results regarding the wind speed characteristics of this area. For the winter test session the four highest probability paths begin or terminate within the area of greatest ground level wind speed. Likewise, for the summer test session three paths were completely bounded within the area of highest ground level wind speed.

What these results signify is that the surface characteristics of this site are actually funneling pedestrians into areas where the ground level wind speeds are highest. This is particularly significant because on test sessions the ground level wind speeds are greater than 20 mph and thus unsafe. This channelling phenomenon is what probably causes this site to be the one most dangerous to pedestrian safety (many pedestrians were observed to encounter balance problems at this site.) Overall, this site is unsuitable for pedestrian movement when ambient wind speeds are greater than 20 mph.

From the analysis of the questionnaire data, subjects at this site perceived this site to have the most extreme wind conditions of the four sites. Respondents working in this area rated this picture the most uncomfortable, windy and exposed. Furthermore, analysis of the attitudinal survey also reveal that subjects at this site rated the picture most offensive on a number of wind environment items.

Site B--Main Egress Location for 600-Foot Office Building.

Although wind speeds at this site are high, pedestrian exposure to the wind speeds are quite short. The most severe wind effects occur within a range of 50 to 80 feet (15 to 25 meters) from the high rise building. Observation of test sessions indicate that average wind speeds of 20 mph (9.1 m/sec) could endanger pedestrians. In general, the wind speeds measured at this location on test days were below the danger limits. However, the wind data recorded at this location on the test days corroborates the results of the questionnaire part of this study, that although "windy", Site B is not perceived to be as windy as Site A.

In contrast to the pedestrian path analyses for Sites A and C, where significant differences are identified between baseline and test days, at Site B no significant differences in path distribution are found for baseline or test sessions. For all six sessions, the distribution of high-probability paths is approximately the same. Area 1 contains the majority of high-probability paths. This space, which is bounded by the main entrance of the office building and the major walkway adjacent to the street, exhibits two general configurations of paths. In every session the majority of paths in this area have at least one endpoint at the boundary of the walkway and the street. The other common configuration in this area is composed of those paths that run parallel to the boundary of the street and the walkway. Each of these six sessions also has at least one path which begins or terminates in area 2. These paths usually emanate from one of the building entrances and are bounded within area 1 or terminate within area 3. Finally, each session has at least one path that traverses area in some manner. Sometimes these paths are bounded within area 3, but usually they begin or terminate in area 2.

Although the path analysis yields no significant results, the velocity analysis reveals significant differences for season. Pedestrian velocity for test days (3.2 ft/sec, 1.0 m/sec) is greater than for baseline days (2.8 ft/sec, 0.9 m/sec). In addition, pedestrian velocity is significantly less during the summer season than during the other seasons of the year. There are no significant density or behavioral differences. Again, this is primarily due to the limited opportunities provided by this urban space for alternate activities.

As this space in many respects is similar to the space adjoining the 500-foot office building, the question arises as to why there are no significant path differences in this space in response to the changing wind conditions. In one urban space (500-foot building/Site A) the differences in the distribution of paths are pronounced under differing wind conditions, whereas for the 600-foot office building (Site B) the distribution of paths remains almost identical across all wind conditions. The answer to this paradox lies in the highly structured environment adjacent to the 600-foot office building space. In contrast to the environment adjacent to the 500-foot building, where there are several distinct alternate pedestrian routes, this urban space is constructed so that pedestrian movement is almost preprogrammed to follow certain routes without any variance. Therefore, the three paths that have been described for Site B are <u>literally</u> the <u>only</u> <u>possible</u> <u>pedestrian</u>

routes that can be followed in the space adjacent to the 600-foot building, regardless of wind conditions. Where pedestrian choice exists as illustrated in the space adjacent to the 500-foot building, differential paths will be chosen and followed in differing wind conditions. However, when the urban space is constructed to limit pedestrian movement, the identical configuration of paths will appear regardless of wind conditions.

The wind contour/path analysis model also emphasizes the fact that the highly structured environment of Site B channels pedestrians to follow only certain routes without any deviation. Unfortunately, five of the high probability paths for the winter test session (the only one investigated for this site under test conditions using the wind contour model) are contained within wind contours where the ground level speeds are unsafe (greater than 20 mph). Therefore, the major pedestrian paths are moving within ground level areas of unsafe wind speed conditions.

The questionnaire data from subjects at City Hall Plaza (Site C) strongly suggest that this space is perceived as both "windy" and "uncomfortable" on the semantic differentials. Confirming this behavioral evaluation is the economic data from two shops located directly within this space. Both shops, which supplied daily receipt data, yielded significant negative correlations ($r = -.76$ and $r = -.65$) relative to daily wind speed as recorded at

Logan Airport. During higher wind speed days lower receipt totals strongly suggest that when pedestrians are considering optional activities (i.e., whether to shop or postpone outside activity), they will defer outside activities and errands during windy days.

Consequently, we are presented with data from three sources that seem to be contradictory. The pedestrian path analysis reveals that the distribution of high-probability paths remains essentially constant throughout all sessions. On the other hand, the space is perceived as windy, uncomfortable, and troublesome when the questionnaire data is analyzed. Finally, the receipt data suggest that shopping is postponed on windy days. Interpreting these diverse data depends on the previous discussion of the particular architectural and landscape features of this space, which allow for only several possible pedestrian routes. Even though pedestrians perceive the space as hazardous, they must still negotiate the identical routes on all days because of the lack of alternatives. However, when dealing with activities that are optional, such as shopping, they will choose to postpone or change their plans rather than negotiate the area on high wind speed days. Data, then, that appear contradictory can be explained in a manner that points out the unusual characteristics of this urban environment.

Site C--City Hall Plaza.

For such areas as open plazas, park benches, or open-air restaurants, the limits of acceptability for the wind environment is considerably lower than those that constitute danger to personal safety. Subjective judgment will determine what is acceptable or nonacceptable. Although it may be considered acceptable to have unpleasant wind conditions in a park one day per week, this could represent a twenty percent loss in revenues for an open-air restaurant and therefore be unacceptable. In this study site it should be noted that mean wind speeds of 5 to 6 mph (2.3 to 2.7 m/sec) were observed to include occasional gusts of 20 to 23 mph (9.1 to 10.5 m/sec). Wind data recorded at this site in general indicates lower wind speeds than at the other three test sites. This is due mainly to the absence of any buildings within 100 to 200 feet of the site.

The path-analysis results from the City Hall Plaza site also display significant differences in the distribution of high-probability paths between baseline and test sessions. The configuration of paths during baseline sessions is more random and diffuse throughout the space than during test sessions. For all test sessions, 72 percent of all high-probability paths are enclosed within one distinct area, while for the winter and spring baseline sessions 28 percent of all paths are enclosed within one area. These percentages correspond closely to the percentage of high-probability paths that traverse area 2, the space adjacent to the entrances of City Hall. Though the baseline and test session figures for the summer are identical, there is a significant difference between these sessions for the other two seasons. For both winter and spring, 72 percent of all paths cross area 2 during the baseline sessions, whereas for the winter and spring test sessions the figures are 28 percent and 42 percent, respectively. Hence, the amount of pedestrian movement adjacent to City Hall (including paths beginning and exiting there) is much greater during baseline days.

Another interesting differences between the two wind conditions is the analysis of paths entering or exiting from the subway station building. Since for all sessions at least one path has an endpoint at this building, this structure provides an excellent reference point for the path analysis in this space. The winter baseline sessions have three such paths, while both the spring and summer baseline sessions have four such paths. A determination of the second endpoint for these paths reveals that 100 percent of the winter, 75 percent of the spring, and 50 percent of the summer paths have their second endpoint at City Hall. However, for the test sessions, none of the paths with one endpoint at the subway station building have their second endpoint at City Hall. On the contrary, for baseline session there is significantly more freedom of movement and greater utilization of the total space compared to test periods. Again, test sessions display a more structured configuration of paths throughout the space.

The pedestrian velocity data also confirms the differential path characteristics of the two wind conditions. Average velocity for baseline periods is significantly slower than test periods. The average baseline velocity across seasons approximately equals the average summer velocity, whereas the average test velocity across seasons equals the average winter velocity. For the density and behavioral analysis of this space, the determining factor is the season of the year rather than session. As this space provides many opportunities for sitting and eating lunch (especially in the summer when many food stands are set up in the plaza for pedestrian convenience), the finding that there are significantly greater densities as well as higher frequencies for all behaviors during the summer sessions is not surprising.

Site D--Boston Commons.

Wind speeds measured at this site were considerably lower than those measured at Sites A and B near tall buildings. The Common lends itself to strolling and sitting, that is, activities that require more comfortable wind conditions and temperatures. It should be pointed out that for Site D sitting may be ruled out during particular seasons because it is either too hot or cold.

Although the Common is fundamentally a recreational area, the actual test site for the study was also located adjacent to a major pedestrian thoroughfare across the Common. Both of these functional characteristics are reflected in the pattern of pedestrian paths. There are significant differences in path distribution between winter and spring test days. For summer sessions no differences are found between test and baseline periods, although this season displays a configuration of high-probability paths different from the other two seasons.

The distribution of paths is more random and diffuse throughout the space during the winter and spring and baseline sessions than during test sessions. For the baseline sessions, 42 percent (winter) and 28 percent (spring) of all high-probability paths are located completely in area 1, the space adjacent to the thoroughfare. For the test sessions the comparable figures are 57 percent (winter) and 72 percent (spring) enclosed within area 1. Therefore, for both test sessions the majority of the paths are located in area 1, whereas for the baseline periods the path distribution extends to areas 2 and 3. Consequently, there are a higher percentage of path crossovers in the baseline sessions and a relatively greater number of paths either beginning or terminating in areas 2 and 3.

In contrast to these two seasons, the distribution of paths in both baseline and test summer sessions shifts strongly to areas 2 and 3. For the baseline period, 42 percent of all paths are encompassed in area 3 and 85 percent of the paths either begin or terminate in areas 2 or 3. For the test session, 29 percent of all paths are enclosed in area 3 and 72 percent of the paths either begin or exit in areas 2 or 3. During the summer session, then, the recreational characteristics of this spcae are the predominant factor regardless of wind conditions. The paths are much more diffuse than in the other seasons, signifying a much greater use of the space.

Both the velocity and density results are similar to data found at the other sites. Pedestrian speeds are slower during baseline sessions, with the slowest speeds recorded during summer. Summer densities are significantly greater than either spring or winter. The frequency of all behaviors is also significantly greater in the summer.

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