A STUDY OF THE WIND ENVIRONMENT IN A CITY CENTER

by

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NOTATION

A	Appendix A or wind environment zone A
a	constant
B	Appendix B or wind environment zone B
b	constant
C	Appendix C or wind environment zone C
D	wind environment zone D or notation for diameter
d	dimentional notation for diameter
E	wind environment zone
F	wind environment zone
f, f_1, f_2	universal functions
h	obstacle height (tube, building, etc.)
h_s	chosen height
I_v	relative gustiness or turbulence intensity
P_v	Probability function of wind speed
R	speed ratio, $R_{max.}$ maximum speed ratio
R_{mean}	mean speed ratio
$R_{r.m.s.}$	root-mean-square speed ratio
T	time interval
t_o	center of time interval T
V	wind speed
$\bar{V}$	mean wind speed
$\bar{V}_g$	gradient wind speed

$\bar{V}_z$	mean wind speed at height z
V_{FM}	fastest mile wind speed at airport at height 6.1 m
V'_{FM}	fastest mile wind speed based on local maximum speed
V''_{FM}	fastest mile wind speed based on local mean speed
$\hat{V}$	peak gust wind speed (maximum wind speed)
V_ℓ	local wind speed at height 1.7 m
$\bar{V}_\ell$	local mean wind speed at height 1.7 m
V_s	velocity at height s
V_t	instantaneous wind speed at time t
V^*_t	wind speed at averaging time t
V_τ	skin friction velocity
V_z	wind speed at height z
V_{3600}	mean hourly wind speed
Z	height above a horizontal reference datum
Z_g	gradient height
α	mean wind speed profile exponent (roughness coefficient)
Δp	pressure difference
$\overline{\Delta p}$	mean of p
$\overline{\Delta p'^2}$	mean square value of p
ν	kinematic visocity of air
ρ	air density
ρ_v	probability density function of wind speed
σ_v	the standard deviation or root-mean-square (r.m.s.) value of deviation of the instantaneous speed from the mean

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Chapter I

INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

The presence of tall structures and high-rise buildings, in the center of a city adjacent to public open spaces, creates local winds at the ground level. Such winds could have an unpleasant or even dangerous influence on people who occupy the outdoor areas existing around those tall buildings.

Observations have shown how winds can affect the comfort and safety of pedestrians. Melbourne and Joubert reported that people had great difficulty balancing themselves at wind speeds of 20 m/s around a tall building of 50 m height at Monash University. Also, people were blown over around the same building at wind speeds of 23 m/s. Penwarden has reported that at wind speed of 25 m/s two elderly ladies died in Great Britain as a result of skull injuries received when blown over by high winds near tall buildings [1].

Adverse wind conditions also reduce the usefulness of outdoor open spaces and plazas. Consequently, significant financial losses, by the owners of these open spaces and plazas, could occur when such places are less used due to the presence of high winds.

1.2 CAUSES OF THE PROBLEM

1.2.1 Mechanism of Flow Around Buildings

The mechanism of flow that lead to windy conditions around a tall building can be explained in the following [1]:

1. When the flow approaches a building, it will separate at the sharp-edged corners of the leading edges of the building. Some of the flow will pass over the building and some will go around the sides (Figure 1.1).
2. The vertical gradient of the local dynamic pressure in the turbulent boundary layer flow creates a downward flow along the front face below the stagnation point which usually occurs around 70 to 80 percent of the building height.
3. This downward flow increases the speed of the accelerated flow around the sides of the building, especially at the ground level. This effect increases with increasing height of the building.

4. In addition, the down flow induces reversed flow and rather windy conditions at the base of the front face. Also, for relatively wide buildings there is a tendency for the formulation of an organized vortex or standing vortex at the base as shown in Figure 1.1.
5. The presence of a lower upstream building can reinforce this upstream vortex and further accelerate ground level wind speeds.
6. Additional accelerated ground level wind speeds can be caused by the existence of constricted areas such as narrow passageways between adjacent buildings, through openings, etc.
7. Finally, the horizontal pressure gradients; from the high pressure areas formed at the base of the windward face to the low pressure areas formed behind the same or an adjacent building (wake regions), contribute to the creation of ground level wind speeds. For the given example of Figure 1.1, the flow directly between these two areas through arcades or around corners causes very high local wind speeds.

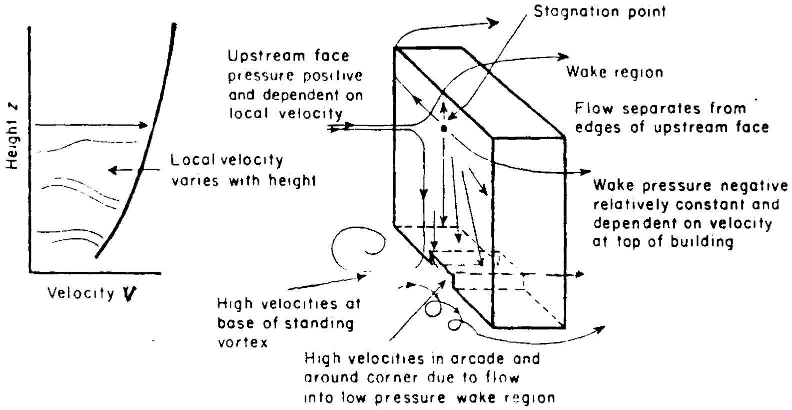


Figure 1.1 Flow field around a building [2].

1.2.2 Effects of Windy Conditions on People

There are two kinds of influences that winds have on people comfort. Reference 3 contains a review of the effect of wind on people as follows:

1. Mechanical Influences of Wind.

   Wind influences comfort mechanically through pressure effects and particle transport. Wind pressure causes disturbance of clothing and hair, resistance to walking, and buffeting of the body and carried objects such as umbrellas. At higher speeds, wind interferes with walking and endangers people by causing them to lose their balance. Eye damage could be caused through dust carried by winds at such velocities. Furthermore, at pedestrian level, wind is accompanied by turbulence which is perceived as varying velocity, gusts, or eddies.

2. Thermal Influences of Wind.

   In cool climates, wind increases the rate of cooling of the body by removing the insulating film of still air found next to skin and clothing in calm conditions. The increased rate of cooling may cause discomfort. In hot climates, the increased wind-induced convection and evaporation may be beneficial to comfort.

1.3 DESIGN CONSIDERATIONS

It must be realized that in order to have a satisfactory wind environment in an urban area, contributions of winds and their effects on people must be considered at the design stage. To achieve this, the designer usually makes use of local wind velocity measurements made on a wind-tunnel model and combines them with meteorological data to determine the frequency of occurrence of certain conditions. These conditions are then compared with published criteria to determine the acceptability of the conditions in the area being studied. However, this is not an easy task since meteorological data are rarely available in a suitable form and the published criteria often use different bases for their recommendations.

1.4 SCOPE OF THIS INVESTIGATION

In this thesis measurements made on a wind-tunnel model of a city center will be combined with meteorological data from a nearby airport in order to describe the expected wind conditions at street level. The acceptability of these conditions will then be determined using various design criteria and conclusions drawn concerning the consistency and applicability of the criteria.

Chapter II

CURRENT STATE OF KNOWLEDGE

2.1 METEROLOGICAL DATA

2.1.1 Ideal Records

Generally, wind conditions of a location are described by the meteorological records provided by the National Weather Service. The data of these records are usually available at some standard height at a nearby airport.

Ideally, the meteorological data should be in the form of a continuous record, i.e., time history of the wind velocity. Any continuous record has the following characteristics [2]:

(1) The mean speed which may be defined, in mathematical form, as

$$\bar{V} = \frac{1}{T} \int_{t_o - T/2}^{t_o + T/2} V_t \, dt \qquad (2.1)$$

where

V_t = the instantaneous wind speed at time t

$\bar{V}$ = the mean speed averaged over some suitable time interval

T = time interval

t_o = center of time interval T

(2) The root mean square (RMS) or standard deviation of wind speed. This is defined as

$$\sigma_v = \{ \frac{1}{T} \int_{t_o-T/2}^{t_o+T/2} (V_t-\bar{V})^2 \, dt \}^{1/2} \qquad (2.2)$$

where

σ_v = the standard deviation or root-mean-square (RMS) value of deviations of the instantaneous speed from the mean.

(3) The relative gustiness or the intensity of turbulence denoted by I is defined as:

$$I_v = \frac{\sigma_v}{\bar{V}} \qquad (2.3)$$

However, one must realize that the speed variations cannot be defined completely by the values of $\bar{V}$ and σ_v, because the variations are random in character and cannot be defined in a deterministic fashion; therefore, it is only possible to define them in a statistical sense. To describe these variations in speed, the probability function, P_v, or its derivative, the probability density function, ρ_v, is used. The function P_v is defined such that: P_v = the probability that the wind speed is less than V. The probability density function is defined such that: ρ_v dV = probability that the speed at some time t lies in the interval V to V + dV. It follows then that the two describing functions are related as follows:

$$\rho_V = \frac{dP_V}{dV} \tag{2.4}$$

It is often assumed that the wind speed in the atmosphere is distributed normally, i.e., Gaussian distribution which is of the form:

$$\rho_V = \frac{1}{(2\pi)^{1/2}\sigma_V} \exp\left[-\frac{1}{2}\left(\frac{V-\bar{V}}{\sigma_V}\right)^2\right] \tag{2.5}$$

Thus, if the mean speed and its standard deviation are known, then the probability of exceedence of a given speed, over a time interval T, can be determined.

A good example to illustrate the above concepts can be found in reference 2. Figure 2.1 shows an anemograph for an extra-tropical cyclone with gust speeds greater than 25 m/s. Figure 2.2 shows an expanded plot of a section of that anemograph where the values of $\bar{V}$ and σ_V are plotted. Figure 2.3 shows the probability distribution of the expanded plot in Figure 2.2. From Figure 2.3, it can be seen that for a mean speed of 22 m/s and a standard deviation of 3.7 m/s a speed of 30 m/s will be exceeded for a total of about 1 min/h

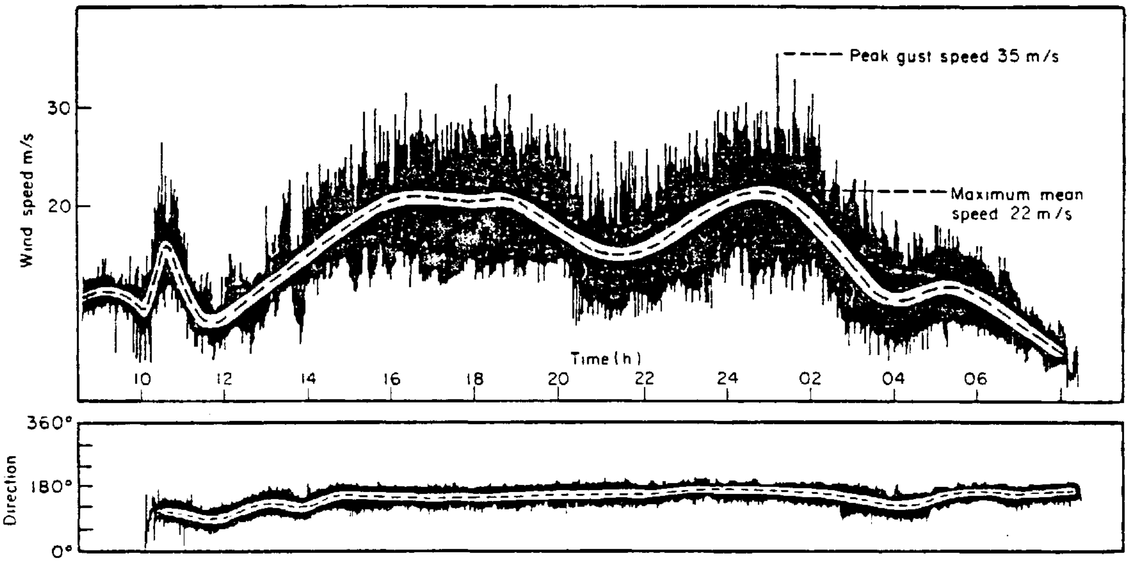


Figure 2.1 The anemograph for an extra-tropical cyclone centered some hundreds of kilometers from the measuring point. Winds gusting in excess of 25 m/s persisted for more than 12 h [2].

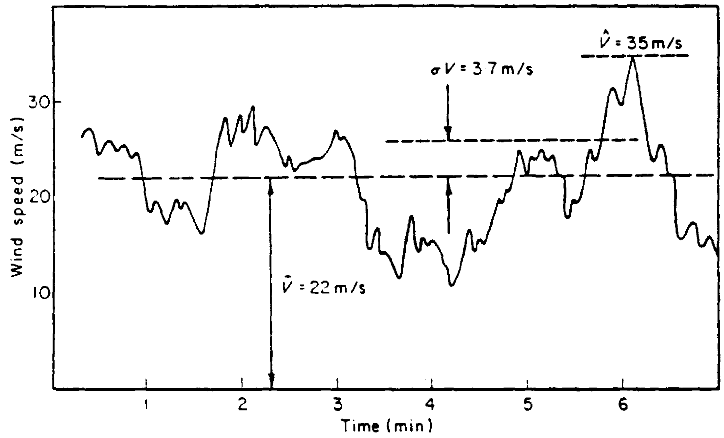


Figure 2.2 Expanded plot of a section of the anemograph of Figure 2.1 [2].

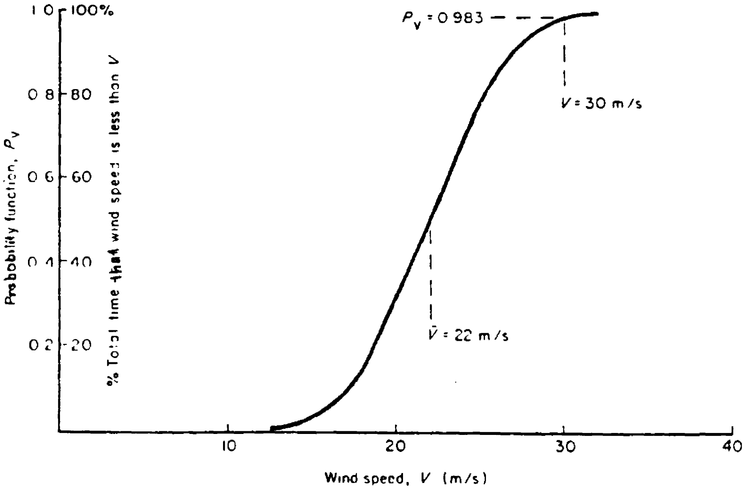


Figure 2.3 Probability distribution of wind speed shown in Figure 2.2 [2].

(i.e., $P_v = 1 - 1/60 = 0.983$). It has been found that [2], typically, for periods of from 10 min to 1 h the peak gust speed, $\hat{V}$, as recorded by most meteorological anemometers (with a response time of 1-3 sec) will exceed the mean by about 3.5 σ_v; i.e.,

$$\hat{V} = \bar{V} + 3.5\ \sigma_v \tag{2.6}$$

That means if we have a turbulence intensity ($\sigma_v/\bar{V}$) of 15% then $\hat{V} = 1.5\ \bar{V}$, and if we have a turbulence intensity of 30% then $\hat{V} = 2.0\ \bar{V}$, etc.

2.1.2 Actual Records

Unfortunately, continuous records are not generally available, which means that the above statistical approach cannot be used. However, the records at most meteorological stations in the U.S.A. are maintained as the fastest mile wind speed and associated direction observed each day. These are published in the monthly summaries of meteorological data provided by the National Weather Service.

The fastest mile wind speed is the inverse of the time in hours for a mile of wind to pass the measuring station. The anemometer is calibrated so that a certain number of revolutions represents such a mile of wind and a mark is made on a time scale each time this number of revolutions is completed. The inverse of the shortest time interval in a given day is the fastest mile wind speed for that day.

2.2 PEDESTRIAN COMFORT CRITERIA

Even though most of the researchers followed different bases in developing pedestrian comfort criteria in a wind environment, they have one thing in common which is that the final decision about the acceptability of certain wind conditions is based on the use of an exceedance probability or frequency of occurrence. Some investigators based their criteria on maximum wind speeds, and others on mean speeds. The following are four of the most extensively used criteria for assessing the acceptability of a wind environment.

1. Murakami [4] based his recommendations on a daily maximum instantaneous speed of 10 m/s at a height of 1.5 m above the ground, proposing Table 2.1. This table divides the wind environment, basically, into three zones. Each zone is associated with a different type of activity depending on how many days/year that the daily maximum instantaneous wind speed 10 m/s is exceeded.

Table 2.1. Acceptable Criteria for Wind Environment Based on Daily Maximum Instantaneous Wind Speed [4].

	Rank 1	Rank 2	Rank 3
Purpose of area	Areas used for purposes most susceptible to wind effects*[1]	Areas used for purposes not too susceptible to wind effects*[2]	Areas used for purposes least susceptible to wind effects*[3]
Limit of exceedance probability	Limit of exceedance probability of 10 m/s (daily maximum instantaneous wind speed)		
	below 10%	below 22%	below 35%
	37 days in a year	80 days in a year	128 days in a year

*[1] for example, outdoor shopping areas, outdoor restaurants, home gardens.

*[2] for example, window shopping or waiting for transportation.

*[3] for example, sidewalks.

2. Melbourne, as reported by Arens [3], suggests the use of annual maximum wind speeds of 10 m/s, 13 m/s, 16 m/s, and 23 m/s based on daylight hours. The criteria were given as follows:

   If the annual maximum wind speed is occurring once per year (based on daylight hours) is

   a. less than 10 m/s, the area is suitable for long stationary exposure, e.g., outdoor restaurants, home gardens,
   b. less than 13 m/s, the area is suitable for short stationary exposure, e.g., window shopping or waiting for transport,
   c. less than 16 m/s, the area is suitable for walking, and
   d. if the annual maximum wind speed exceeds 23 m/s, the area is considered dangerous.

3. Davenport, also reported by Arens [3], recommended the use of hourly mean wind speeds of 3.5 m/s, 5.5 m/s, 7.5 m/s, and 10 m/s and based his criteria on daylight hours and a turbulence intensity of 15%. His criteria are:

Criteria	Probability of Exceeding Hourly Mean Wind Speed
Acceptable for:	
walking fast	If $P[\bar{V} > 10] < 0.05$
strolling	If $P[\bar{V} > 7.5] < 0.05$
standing, sitting short exposure	If $P[\bar{V} > 5.5] < 0.05$
standing, sitting long exposure	If $P[\bar{V} > 3.5] < 0.05$

4. Penwarden [2], using a different approach, reported that if the frequency of occurrence of a mean wind speed in excess of 5 m/s exceeds 20% of the time (i.e., 876 daylight hours per annum) protective measures are likely to be needed; between 10% and 20% complaint is likely but may be insufficient to provoke actions, and below 10% (438 daylight hours per annum) conditions are likely to be satisfactory. However, the averaging time of the wind speed was not reported.

It can be seen from the above criteria that there are considerable differences in the manner in which the criteria are presented, both in terms of type of speed (peak or mean) and in the occurrence rate or duration.

2.3 WIND TUNNEL TECHNIQUES

2.3.1 Introduction

In order to assess the wind environment created by a proposed building configuration, tests are often conducted in a boundary layer wind tinnel.

Although there are differences between individual boundary layer wind tunnel techniques, most of them have the following common features when used to study local wind speeds in an urban area.

1. A boundary layer with suitable velocity profile and turbulence level is created by various types of obstructions in the approaching flow.
2. A scale model of the area under consideration is mounted on a turntable.
3. Appropriate velocity sensors are used to measure local velocities close to the flow of the wind tunnel.

2.3.2 The Boundary Layer

In general, the velocity profile, turbulence intensity and depth of the earth's boundary layer will depend on the ground roughness. At or above the boundary layer at a height Z , the wind velocity depends solely on pressure gradients in the atmosphere and is invariant with height. This velocity, $\bar{V}_g$, is called the gradient wind speed and height, Z_g, the gradient height.

If the mean speed at a given height, Z, is $\bar{V}_z$ and the gradient wind speed at the top of the boundary layer, height Z_g, is $\bar{V}_g$, then the variation of $\bar{V}_z$ with height can be approximated by a number of mathematical expressions. The most commonly used of these is the 'Power Law' [2], which can be represented as:

$$\bar{V}_z = \bar{V}_g \left(\frac{Z}{Z_g}\right)^{\alpha} \tag{2.7}$$

in which Z_g and α are functions of ground roughness. The symbol is called the mean speed exponent or, sometimes, roughness coefficient. As might be expected, the rougher the terrain the greater the value of Z_g and the more pronounced the effect of boundary shear, i.e., the greater the value of α. In a wind tunnel an attempt is usually made to recreate a boundary layer appropriate to the approach conditions of the area under investigation.

2.4 VELOCITY MEASURING DEVICES

When studying a wind environment around a building, it has been common practice to use either small pitot-static tubes or hot wire anemometers. However, recently, a simple omnidirectional sensor using standard automated pressure measuring equipment has been developed at the National Research Council in Canada.

2.4.1 The Pitot-Static Tube and Hot Wire Anemometer

The small pitot-static tubes are easy to use and require little sophisticated equipment if mean velocities only are to be measured. However, if maximum velocities are to be determined, more sophisticated equipment is required. For both types of measurements, the tube must be rotated so that it faces directly into the flow. Although this procedure does provide information about the wind conditions, it is very time consuming.

Hot wire equipment is highly sophisticated and delicate. Its main advantage is that when used with the wire vertical, the model can be rotated for different wind directions without any further adjustment of the probe because of the independency of the hot wire on wind direction when recording velocity. For the same reason, it is disadvantageous because it does not provide the local wind direction.

Furthermore, whenever the wind environment has a turbulence intensity above 30%, the mean velocity measured by the hot wire is quite unreliable. This is because of the fact that the hot wire is insensitive to wind direction in the plane normal to the wire, hence, a reversed flow appears as a positive addition to the mean velocity. However, the problem is almost avoided if only peak velocities are measured because there is no dependence on a mean velocity measurement. Finally, the use of hot wire and equipment associated with it is quite expensive.

2.4.2 The Simple Omnidirectional Sensor

This is sometimes referred to as a surface wind sensor. Geometrical details [5] are shown in Figure 2.4. It consists of a hole of diameter D and a tube of external diameter d, slightly less than D, coming out through the hole above the model street surface to a height h (few mm above the street surface). This tube has a flat top. The excess pressure ΔP at the bottom of the sensor hole over that at the top of the sensor tube is measured and from P the wind speed at a chosen height h_s above the surface can be calculated using an appropriate calibration formula.

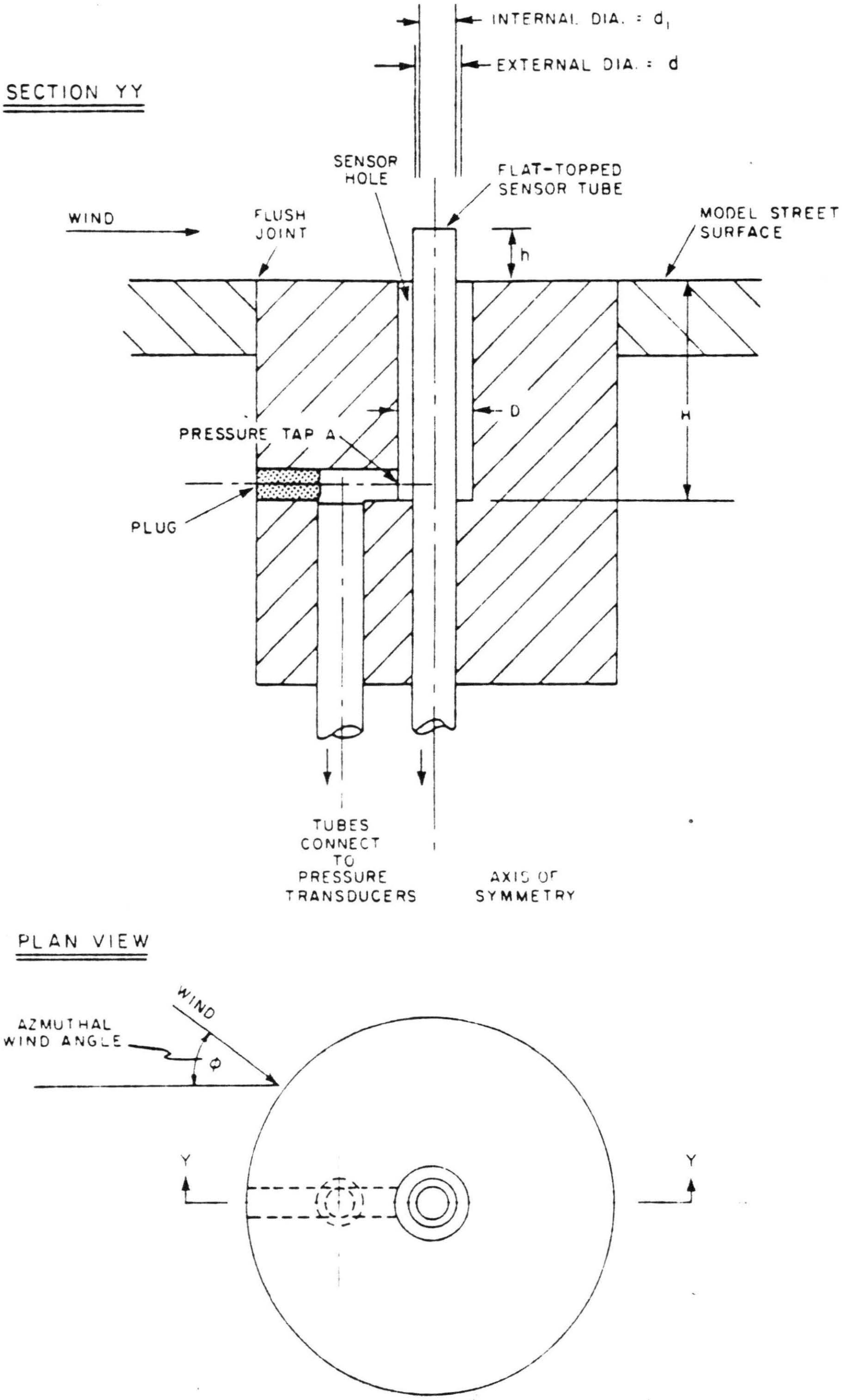


Figure 2.4 Geometry of the surface wind sensor [5].

In a turbulent boundary layer on a smooth flat surface, it is well established that in the region very close to the surface the mean velocity profile is controlled by the following universal law:

$$\bar{V} = V_\tau \ f(V_\tau \frac{Z}{\nu}) \tag{2.8}$$

where

$\bar{V}$ is the mean velocity,

V_τ the skin friction velocity,

Z the distance from the surface,

ν the air kinematic viscosity, and

f is a universal function that is independent of the local pressure gradient or flow acceleration.

Because of the conformity of the mean velocity to the universal law, the mean pressure distribution over a small obstacle, of given shape, immersed in the wall-law region also conforms to a universal law. Therefore, the mean pressure difference ΔP between two points on the obstacle will obey the following law:

$$\Delta p h^2/\rho \nu^2 = f_1(v_\tau \ h/_\nu) \tag{2.9}$$

where f_1 is a universal function and h is the obstacle's height. Using Eqns. (2.8) and (2.9) the skin friction velocity V_τ can be eliminated. This results in the following relation between Δp and the mean velocity v_s at some height h_s within the wall-law region:

$$\Delta p\, h^2/\rho \nu^2 = f_2 (V_s\, h/_\nu\, ,\; h_s/h) \qquad (2.10)$$

Hence, if f_2 is known, the obstacle, which in this case is the sensor (Figure 2.4), can be turned into a velocity meter since Eqn. (2.10) gives the means of calculating V_s from measurements of Δp.

However, it can be shown, as explained in reference 5, that the relationship hold equally well for instantaneous velocities and instantaneous pressure drops Δp. In general, the wind speed V will be given by the form

$$V = a + b\sqrt{\Delta p} \qquad (2.11)$$

where a and b are constants, also this form may be used to measure peak velocities. Time-averaged values of $\bar{V}$ and σ_v may be obtained, respectively, from

$$\bar{V} = a + b[\overline{\Delta p} - \frac{1}{4} (\overline{\Delta p'^2}/\overline{\Delta p})]^{1/2} \qquad (2.12)$$

and

$$\sigma_v = \frac{b}{2} (\overline{\Delta p'^2}/\overline{\Delta p})^{1/2} \qquad (2.13)$$

where $\overline{\Delta p}$ is mean of Δp and $\overline{\Delta p'^2}$ is the mean square value of Δp.

Some of the advantages of using the surface wind sensor are that it is independent of direction; can be readily calibrated using a hot wire anemometer; and since it is cheap and easy to make, it can be deployed in large numbers and connected to standard pressure measuring equipment. When used in this way with automated scanivalve equipment, pedestrian level wind conditions can be mapped in order of magnitude faster than with hot-wire or pitot-tube methods.

Chapter III

WIND TUNNEL EXPERIMENT

3.1 DESCRIPTION OF WIND TUNNEL

The experimental part of the present investigation was carried out in the Stability Wind Tunnel at Virginia Polytechnic Institute and State University. This wind tunnel has a working section of 1.8 m by 1.8 m in which a boundary layer is created. A group of spires installed at the entrance of this section followed by a set of 50 mm and 100 mm foam cubes develop the desired velocity profile and the level of turbulence. The velocity profile that was generated in this experiment was in accordance with "power law", Eqn. (2.7), i.e.,

$$\bar{V}_z = \bar{V}_g\left(\frac{Z}{Z_g}\right)^{\alpha}$$

The profile used in this experiment had a full-scale gradient height of 427 m and roughness coefficient of 0.31. This velocity profile and its other characteristics were considered appropriate for the approaching flow to the center of the city of Charlotte, North Carolina, which was modeled in this experiment. Further details of the wind tunnel and the boundary layer's simulations can be found in references 6 and 7.

3.2 DESCRIPTION OF WIND TUNNEL MODEL

As part of a more comprehensive study of the wind effects on a proposed development in Charlotte, NC, models of existing and proposed buildings were constructed at a scale of 1/240 over an area of 366 m diameter centered on the new development [6]. All of these models were attached to a turntable of 1.52 m diameter. This scale was chosen since it enabled most of the adjacent significant structures to be modelled. However, for some wind direction, additional high-rise buildings were added to the upstream roughness elements when considered necessary. Photographs of the model in the Stability Wind Tunnel of VPI & SU are shown in Figure 3.1. Figure 3.2 shows the layout and heights of buildings in the city center of Charlotte, NC.

3.3 MODEL MEASUREMENTS

In this experiment, forty-five surface wind sensors were used on the model (45 locations). The tubes of these devices were connected to a standard scanivalve pressure measuring system used in the wind tunnel. After checking the calibration of the devices using a hot wire anemometer, records of at least 6 seconds were made for each sensor at each wind direction. These records were digitized at 200

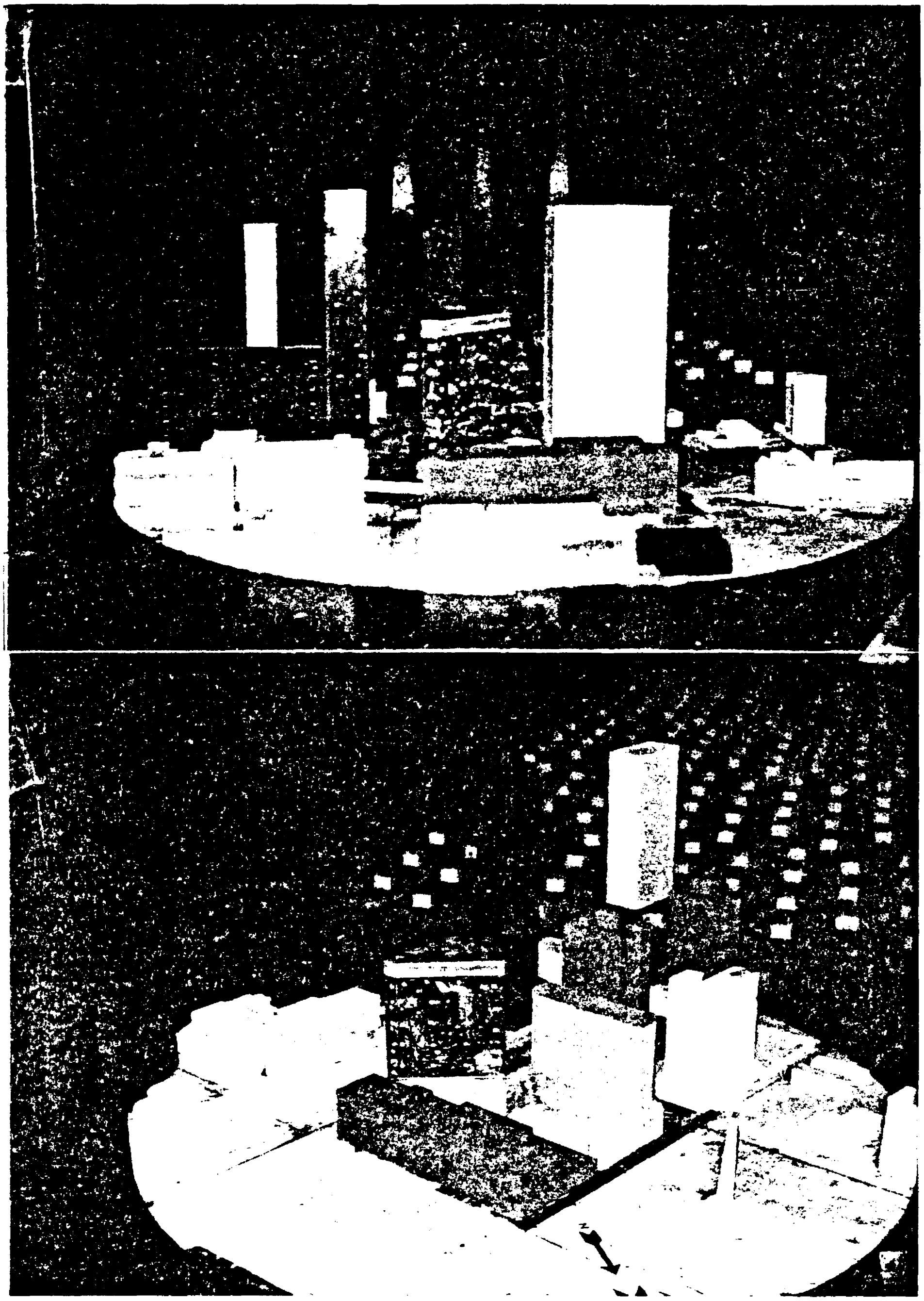


Figure 3.1 Model buildings of the city center of Charlotte, NC, in the Stability Wind Tunnel of VPI & SU.

Figure 3.2 Layout of city center of Charlotte, NC.

samples per second and stored using a Hewlett-Packard 3052A Data Acquisition System.

3.4 RESULTS OF THE EXPERIMENT

The stored data were converted to mean, r.m.s. and peak wind speeds at a scale height of approximately 1.7 m above the surface of the streets. These speeds were then converted into mean, r.m.s., and peak speed ratios by dividing them by the mean speed at the scale height of 1.7 m in the approaching boundary layer. This gave a measure of the magnification of speeds in comparison with conditions undisturbed by the large buildings in the city center. However, the wind speed at the scale height of 1.7 m in the approaching flow was not measured during these tests but was deduced from the speed measured at the wind tunnel pitot tube which is at a scale height of 360 m above the street level. The locations of the sensors and the corresponding speed ratios were mapped, using the data acquisition system, as follows:

1) maximum speed ratios, $R_{max.}$, (Appendix A),
2) mean speed ratios, R_{mean}, (Appendix B), and
3) r.m.s. speed ratios, $R_{r.m.s.}$, (Appendix C).

Note:

Recordings were made at either 15° or 30° increments of wind angle. For the purposes of this study only wind angles available in the meteorological records are used, i.e., 45° increments from North. Therefore, Appendices A, B, and C only include the values of Rmax., Rmean, and Rr.m.s. for 45° increments of wind direction. However, no direct measurements were made for the angles 135° and 225°. Instead, the angles 120° and 150° were averaged to give values of R for the angle 135°, and the angles 210° and 240° were averaged to give values of R for the angle 225°. Appendices A, B, and C, therefore, also include values for 120°, 150°, 210°, and 240°.

Chapter IV

ANALYSIS OF RESULTS

4.1 METEOROLOGICAL DATA FOR CHARLOTTE, NC

As mentioned earlier, the best data normally available from a meteorological station is the daily fastest mile wind speed (m.p.h.). The nearest station to the center of Charlotte is at Douglas Municipal Airport which is about 9.6 km west of the buildings under consideration. Here measurements of wind conditions are made at a height of 6.1 m. Daily records show the fastest mile wind speed and its direction to the nearest of 8 compass points. A typical example of the data provided for one month is given in Table 4.1. Although it is a convenient way of measuring extreme data, care must be taken in comparing the fastest mile wind speed with the other forms of data such as mean hourly wind speeds or 2-3 second gusts. The fastest mile speed, being the inverse of the time for a mile of wind to pass the anemometer, has an averaging time which varies with speed.

For the purpose of the present analysis, data for the five year period: January 1974 through December 1978, were considered. January 1974 was the earliest date that monthly summaries were readily available, and in 1979 the method of

Table 4.1 Sample of the Meteorological Data.

LOCAL CLIMATOLOGICAL DATA

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
ENVIRONMENTAL DATA SERVICE

CHARLOTTE, NORTH CAROLINA
NATIONAL WEATHER SERVICE OFC
DOUGLAS MUNICIPAL AIRPORT
FEBRUARY 1974

LATITUDE 35° 13′ N LONGITUDE 80° 56′ W ELEVATION (GROUND) 736 FT. STANDARD TIME USED: EASTERN WBAN #13881

DATE	TEMPERATURE °F							WEATHER TYPES ON DATES OF OCCURRENCE	SNOW, ICE PELLETS OR ICE ON GROUND AT 07AM IN.	PRECIPITATION		AVG. STATION PRESSURE IN. ELEV. 769 FEET M.S.L.	WIND					SUNSHINE		SKY COVER TENTHS		DATE
	MAXIMUM	MINIMUM	AVERAGE	DEPARTURE FROM NORMAL	AVERAGE DEW POINT	DEGREE DAYS BASE 65° HEATING	DEGREE DAYS BASE 65° COOLING	1 FOG 2 HEAVY FOG X 3 THUNDERSTORM 4 ICE PELLETS 5 HAIL 6 GLAZE 7 DUSTSTORM 8 SMOKE, HAZE 9 BLOWING SNOW		WATER EQUIVALENT IN	SNOW, ICE PELLETS IN.		RESULTANT DIRECTION	RESULTANT SPEED M.P.H.	AVERAGE SPEED M.P.H.	FASTEST MILE SPEED M.P.H.	FASTEST MILE DIRECTION	HOURS AND TENTHS	PERCENT OF POSSIBLE	SUNRISE TO SUNSET	MIDNIGHT TO MIDNIGHT	
1	2	3	4	5	6	7A	7B	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	68	36	52	9	37	13	0	8	0	0	0	29.23	15	4.7	7.8	14	SW	10.5	100	0	1	1
2	68*	48	58*	15	52	7	0	23 8	0	1.57	0	29.01	21	3.9	8.6	16	SW	0.5	5	10	10	2
3	67	41	54	11	53	11	0	1 3	0	.08	0	28.92	25	4.3	10.6	17	N	3.0	28	9	9	3
4	48	30	39	-4	23	26	0		0	0	0	29.17	31	9.0	11.1	17	SW	9.9	94	3	2	4
5	48	25	37	-6	15	28	0		0	0	0	28.43	13	3.2	6.6	11	SW	10.6	100	0	0	5
6	44	32	38	-5	34	27	0	1 8	0	.54	0	29.33	01	.8	6.2	12	S	0.0	0	10	9	6
7	54	43	49	6	49	16	0	2	0	.22	0	28.02	19	2.2	7.2	11	NE	0.0	0	10	10	7
8	52	33	43	0	35	22	0	1 8	0	.62	0	28.91	36	7.7	10.2	19	N	0.0	0	10	10	8
9	40	25	33	-10	19	32	0		0	T	T	29.19	33	3.6	6.8	12	N	9.5	89	3	4	9
10	44	23	34	-9	19	31	0		0	T	T	29.27	23	4.2	8.2	18	SW	10.8	100	0	2	10
11	51	28	40	-3	18	25	0		0	0	0	29.22	29	7.2	9.4	15	NW	10.8	100	0	1	11
12	61	25	43	-1	22	22	0		0	0	0	29.31	19	5.2	7.1	13	SW	10.8	100	0	0	12
13	66	33	50	6	33	15	0		0	0	0	29.20	20	11.7	11.9	27	SW	9.9	91	3	2	13
14	60	48	54	10	48	11	0	1	0	.14	0	29.17	20	7.5	9.2	14	SW	2.7	25	10	9	14
15	54	38	46	2	42	19	0	1 8	0	.01	0	29.28	06	6.9	10.4	17	E	1.3	12	10	10	15
16	39	31	35	-9	30	30	0	1 6 8	0	.92	0	29.06	01	6.9	10.5	20	NE	0.0	0	10	9	16
17	56	31	44	0	24	21	0		0	0	0	29.04	29	8.7	9.9	16	W	11.0	100	0	0	17
18	56	28	42	-2	23	23	0		0	0	0	29.14	13	2.2	6.0	11	S	7.7	70	8	7	18
19	61	45	53	9	44	12	0	1	0	.31	0	28.75	18	8.9	11.1	23	W	0.3	2	9	8	19
20	61	39	50	5	34	15	0		0	0	0	29.09	24	5.0	9.2	15	W	11.1	100	0	0	20
21	66	37	52	7	36	13	0		0	.01	0	29.36	09	7.1	10.4	19	SE	10.4	93	4	4	21
22	63	41	52	7	44	13	0	1 3	0	.48	0	28.91	20	17.3	19.4	36	SW	8.1	73	5	6	22
23	58	30	44	-1	22	21	0		0	0	0	29.26	23	5.5	7.2	11	W	11.2	100	5	3	23
24	59	34	47	2	30	18	0		0	0	0	29.22	18	8.1	9.8	18	S	5.9	52	8	4	24
25	48	22	35	-10	12	30	0		0	0	0	29.28	29	11.3	11.8	19	W	10.4	92	3	1	25
26	43	17*	30*	-16	6	35	0		0	0	0	29.54	33	5.8	7.3	12	W	11.3	100	0	0	26
27	54	20	37	-9	14	28	0	8	0	0	0	29.59	15	3.2	7.8	12	S	11.4	100	2	1	27
28	63	29	46	0	19	19	0		0	0	0	29.47	19	12.3	13.1	23	SW	10.4	92	9	5	28
	SUM	SUM				TOTAL	TOTAL			TOTAL	TOTAL	FOR THE MONTH:						TOTAL	%	SUM	SUM	
	1552	912				583	0	NUMBER OF DAYS		4.90	T	29.19	22	2.6	9.4	36	SW	199.5	FOR	141	127	
	AVG.	AVG.	AVG.	DEP.	AVG.	DEP.	DEP.	PRECIPITATION		DEP.						DATE: 22		POSSIBLE	MONTH	AVG.	AVG.	
	55.4	32.6	44.0	0.0	30	-5	0	≥ .01 INCH 11		1.07								305.8	65	5.0	4.5	

				SEASON TO DATE		SNOW, ICE PELLETS							
NUMBER OF DAYS				TOTAL	TOTAL	≥ 1.0 INCH	0	GREATEST IN 24 HOURS AND DATES				GREATEST DEPTH ON GROUND OF SNOW, ICE PELLETS OR ICE AND DATE	
MAXIMUM TEMP.		MINIMUM TEMP.		2248	0	THUNDERSTORMS	3	PRECIPITATION		SNOW, ICE PELLETS			
≥ 90°	≤ 32°	≤ 32°	≤ 0°	DEP.	DEP.	HEAVY FOG X	2	1.57	2	T	10+	0	
0	0	15	0	-330	0	CLEAR 13	PARTLY CLOUDY 3	CLOUDY 12					

recording directions was changed. Use of data after that date would have complicated the analysis. A five year period was also thought to be a sufficiently long period to be statistically meaningful.

4.2 COMBINATION OF METEOROLOGICAL DATA WITH WIND-TUNNEL RESULTS

In order to use the data provided by the National Weather Service in conjunction with the speed ratios obtained in the wind-tunnel test, it was necessary to reduce the fastest mile wind speeds measured at the airport at 6.1 m to an equivalent mean hourly wind speed at 1.7 m in the modelled boundary layer. However, since the power law (Eqn. 2.7) is only satisfactory for velocities averaged over a reasonable period of time, the fastest mile wind speed at the airport had first to be converted to an equivalent mean hourly wind speed. This was done by reference to the results of Durst [9]. His relationship between mean hourly wind speeds (V_{3600}) and other averaging times (V_t^*) is given in Figure 4.1.

As was pointed out earlier, the averaging time varies with fastest mile wind speed. For the analysis which follows, the lowest fastest mile speed used was 9 mph representing an averaging time of 3600/9 = 400 sec, and the high-

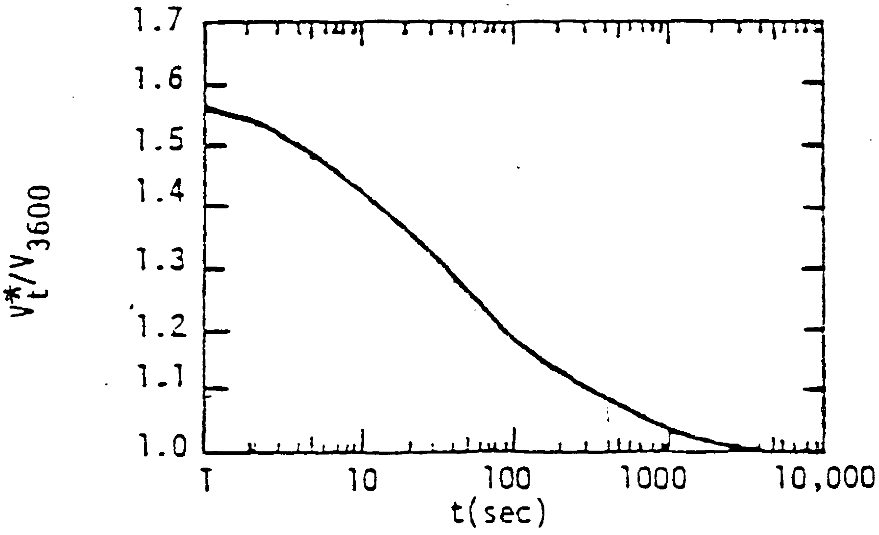


Figure 4.1 Ratio of probable maximum speed averaged over t secs to hourly mean speed [9].

est fastest mile speed used was 50 mph with an averaging time of 3600/50 = 72 sec. According to Durst for an averaging time of 400 sec, $V_{3600} = 0.92\ V^*_{400}$, and for an averaging time of 72 sec, $V_{3600} = 0.82\ V^*_{72}$.

Varying this conversion factor would have introduced considerable computational difficulty, so considering the tentative nature of the application of Durst's result, it was decided to use only one conversion factor so that

$$V_{3600} = 0.85\ V_{FM}\ . \tag{4.1}$$

or
$$\bar{V}_{airport} = 0.85\ V_{FM} \tag{4.2}$$

where $V_{airport}$ is the mean hourly wind speed and V_{FM} is the fastest mile wind speed; both speeds are at the airport at height of 6.1 m. The mean hourly wind speed at the airport was then converted to a gradient speed. The gradient height at the airport was taken to be 274 m and the power law exponent $\alpha = 0.14$, i.e., open country as defined in reference 8. This gradient speed was then reduced to 1.7 m in the approach boundary layer where the gradient height was 427 m and the exponent $\alpha = 0.31$. Using Eqn. 2.7,

$$\bar{V}_\ell = \bar{V}_{airport}\left(\frac{274}{6.1}\right)^{0.14}\left(\frac{1.7}{427}\right)^{0.31}$$

$$\bar{V}_\ell = 0.31 \times 0.85\ V_{FM} \tag{4.3}$$

where $\bar{V}_\ell$ is the local mean wind speed at height of 1.7 m in the approach flow. Recalling that the ratio, R, is the local speed normalized with respect to the mean speed at 1.7 m in the approach flow, one can compute the maximum or mean speed (depending on R) at a given location near the city center by the equation

$$V_\ell = 0.31 \times 0.85\ V_{FM} \times R \tag{4.4}$$

where V_ℓ is the local wind speed at height 1.7 m, and R can be $R_{max.}$ or R_{mean} or $R_{r.m.s.}$ as appropriate.

It is important to realize that although the speed at 1.7 m is used as a basis for the speed ratios, the actual reference point was the pitot tube at a scale height of 360 m virtually at the top of the boundary layer. Thus, even if the full scale velocity profile does not agree with that measured in the wind tunnel, the actual local flows, which are controlled by the building arrangement, are unlikely to differ significantly from those measured in the wind tunnel.

4.3 INTERPRETATION OF CRITERIA

In order to compare the criteria introduced in Chapter II, a unified standard classification, incorporating the specifications of these criteria, has been developed to describe the type of activity that could be conducted in the wind environment in a particular zone. Table 4.2 gives details of these zones.

Reclassifying the criteria from Chapter II and considering the fact that these criteria are based on daylight hours and the meteorological data does not differentiate between night and day occurrences, the following interpretations of the criteria, in accordance with Table 4.2, can be made.

1. Murakami

Zone	Condition
E	$\hat{V} > 10$ m/s more than 128 days/year.
D	$\hat{V} > 10$ m/s between 80 and 128 days/year.
C	$\hat{V} > 10$ m/s between 37 and 80 days/year.
A/B	$\hat{V} > 10$ m/s less than 37 days/year.

2. Melbourne

Zone	Condition
F	$\hat{V} > 23$ m/s more than 2 days/year.
E	23 m/s $> \hat{V} >$ 16 m/s more than 2 days/year.

Table 4.2 Wind Environment Zones & Activities.

Zone	A	B	C	D	E	F
Activity	Suitable for long exposure, sitting or standing.	Suitable for short exposure, sitting or standing.	Suitable for strolling.	Suitable for walking.	Unacceptable but not dangerous.	Dangerous.

D	16 m/s > $\hat{V}$ > 13 m/s more than 2 days/year.
C/B	13 m/s > $\hat{V}$ > 10 m/s more than 2 days/year.
A	$\hat{V}$ > 10 m/s less than 2 days/year.

Melbourne's criteria actually refer to maximum annual wind speeds based on daylight hours. The wind data does not differentiate between night and day, so it is assumed that two occurrences per year are equivalent to one during daylight hours. The assumption is also made here that a peak speed exceeding the criterion occurs only once in a given day.

3. Davenport

Zone	Condition
E/F	$\bar{V}$ > 10 m/s more than 37 days/year.
D	10 m/s > $\bar{V}$ > 7.5 m/s more than 37 days/year.
C	7.5 m/s > $\bar{V}$ > 5 m/s more than 37 days/year.
B/A	$\bar{V}$ > 5 m/s less than 37 days/year.

Davenport expresses his criteria in terms of percentage of time the mean hourly wind speed exceeds a particular value. The assumption made here is that if the mean hourly wind speed on a given day, based on the fastest mile wind speed, exceeds the criteria, then the whole day can be considered as the period in which the criterion is exceeded.

4. Penwarden

Because of the insufficient details that Penwarden gave, Table 4.2 could not be applied directly to his criteria. However, it is worthwhile to include his results in this paper for later comparison. Penwarden claims that if rate of occurrence of the mean wind speed (assumed hourly) in excess of 5 m/s is

a. greater than 146 days/year, then protective measures are likely to be needed;
b. between 73 days/year and 146 days/year, then complaint is likely but may be insufficient to provoke actions;
c. less than 73 days/year, then conditions are likely to be satisfactory.

Penwarden also expresses his criteria in terms of percentage of time. The same assumption was made here as with Davenport's criteria in converting percentage of time to days/year. Also, since both Davenport and Penwarden based their recommendations on daylight hours, the same assumption was made as in Melbourne's criteria.

4.4 DETERMINING THE RATE OF OCCURRENCE

From the above interpretations of comfort criteria, it appears that there is a certain number of days per year that a certain speed must not be exceeded to have acceptable wind conditions. This speed varies from one criterion to another. Since the records related to the present study are available in the form of fastest mile wind speed, then equation 4.4 can be used to determine the fastest mile wind speed at the airport necessary to produce a given local wind speed, i.e.,

$$V_{FM} = \frac{V_\ell}{0.31 \times 0.85 \times R} \tag{4.5}$$

here V_ℓ is the local criterion speed and R is the appropriate speed ratio. Thus, if a maximum (or mean) local speed is considered and $R_{max.}$ (or R_{mean}) is obtained from Appendix A (or Appendix B), then the corresponding V_{FM} can be computed from equation 4.5. Next, for a given value of V_{FM}, a search can be made through the 5-year period meteorological records to find how many times this value has been exceeded. From this, the average rate of exceedance per year can be determined. A judgment can then be made about the wind conditions by comparing this rate of exceedance with existing criteria.

4.4.1 Example

The following example illustrates the procedure used to determine the rate of occurrence. Consider location #6 adjacent to North Carolina National Bank:

(1) Going through Appendices A and B, one can tabulate values of $R_{max.}$ and R_{mean} that correspond to location #6 in all directions (see Table 4.3).

(2) It was noticed that most of the existing criteria are based on:

a. A maximum local speed of the values:

$\hat{V}_1 = 10$ m/s, $\hat{V}_2 = 13$ m/s, $\hat{V}_3 = 16$ m/s, $\hat{V}_4 = 23$ m/s,

b. a mean local speed of the values:

$\bar{V}_1 = 5$ m/s, $\bar{V}_2 = 7.5$ m/s, $\bar{V}_3 = 10$ m/s.

All of these values are converted to equivalent fastest mile wind speeds at the airport to give values of V_ℓ, and with the appropriate values of $R_{max.}$ or R_{mean} substituted in Eqn. 4.5. The results are recorded in Table 4.3 as V'_{FM1}, V'_{FM2}, V'_{FM3}, and V'_{FM4} for maximum speeds, and as V''_{FM1}, V''_{FM2}, and V''_{FM3} for mean speeds.

(3) Then, for each wind direction recorded in the wind data, a search was made for occurrences which fitted the criteria. These are recorded in Table 4.4.

Table 4.3. Equivalent Fastest Mile Wind Speed (mph) at the Airport for each Direction at Location #6.

Direction	$R_{max.}$	V'_{FM1}	V'_{FM2}	V'_{FM3}	V'_{FM4}	R_{mean}	V''_{FM1}	V''_{FM2}	V''_{FM3}
N (0.0°)	2.95	28	37	45	65	1.78	23	35	47
NE (45°)	4.01	21	27	33	48	2.68	15	23	31
E (90°)	4.34	19	25	31	44	3.09	13	20	27
SE (135°)	5.84	14	19	23	33	4.66	9	13	18
S (180°)	4.58	18	24	29	42	3.73	11	17	22
SW (225°)	4.72	18	23	28	41	3.50	12	18	24
W (270°)	3.88	21	28	34	50	1.55	27	40	54
NW (315°)	2.30	36	47	58	84	1.24	34	50	67

Table 4.4. Number of Days Given Wind Speeds Exceeded at Location #6 (5-year period).

Directions, V'_{FM}, & V''_{FM} (mph)	$V_{FM}\geq V'_{FM1}$	$V_{FM}\geq V'_{FM2}$	$V_{FM}\geq V'_{FM3}$	$V_{FM}\geq V'_{FM4}$	$V_{FM}\geq V''_{FM1}$	$V_{FM}\geq V''_{FM2}$	$V_{FM}\geq V''_{FM3}$
N $V'_{FM1}=28$, $V'_{FM2}=37$, $V'_{FM3}=45$, $V'_{FM4}=65$ $V''_{FM1}=23$, $V''_{FM2}=35$, $V''_{FM3}=47$	3	None	None	None	11	None	None
NE $V'_{FM1}=21$, $V'_{FM2}=27$, $V'_{FM3}=33$, $V'_{FM4}=48$ $V''_{FM1}=15$, $V''_{FM2}=23$, $V''_{FM3}=31$	12	1	None	None	123	8	None
E $V'_{FM1}=19$, $V'_{FM2}=25$, $V'_{FM3}=31$, $V'_{FM4}=44$ $V''_{FM1}=13$, $V''_{FM2}=20$, $V''_{FM3}=27$	3	3	1	None	20	3	3
SE $V'_{FM1}=14$, $V'_{FM2}=19$, $V'_{FM3}=23$, $V'_{FM4}=33$ $V''_{FM1}=9$, $V''_{FM2}=13$, $V''_{FM3}=18$	47	20	10	1	119	63	22

Table 4.4. Number of Days Given Wind Speeds Exceeded at Location #6 (5-year period) (continued).

Directions, V'_{FM}, & V''_{FM} (mph)	$V_{FM}\geq V'_{FM1}$	$V_{FM}\geq V'_{FM2}$	$V_{FM}\geq V'_{FM3}$	$V_{FM}\geq V'_{FM4}$	$V_{FM}\geq V''_{FM1}$	$V_{FM}\geq V''_{FM2}$	$V_{FM}\geq V''_{FM3}$
S $V'_{FM1}=18$, $V'_{FM2}=24$, $V'_{FM3}=29$, $V'_{FM4}=42$ $V''_{FM1}=11$, $V''_{FM2}=17$, $V''_{FM3}=22$	33	10	4	None	156	50	15
SW $V'_{FM1}=18$, $V'_{FM2}=23$, $V'_{FM3}=28$, $V'_{FM4}=41$ $V''_{FM1}=12$, $V''_{FM2}=18$, $V''_{FM3}=24$	153	70	31	6	371	153	56
W $V'_{FM1}=21$, $V'_{FM2}=28$, $V'_{FM3}=34$, $V'_{FM4}=50$ $V''_{FM1}=27$, $V''_{FM2}=40$, $V''_{FM3}=54$	26	4	1	None	6	None	None
NW $V'_{FM1}=36$, $V'_{FM2}=47$, $V'_{FM3}=58$, $V'_{FM4}=84$ $V''_{FM1}=34$, $V''_{FM2}=50$, $V''_{FM3}=67$	4	None	None	None	4	None	None
	281	108	47	7	810	277	96

(4) Finally, adding all values in every separate column of Table 4.4 resulted in the number of days that a certain speed was exceeded in the five year period. Next, dividing this by five, the rate of occurrence per year was obtained. For the above example, the values obtained by adding every column, separately, are recorded in the last row of Table 4.4. Dividing these values by five we obtained the following results:

a. based on maximum speeds.

Criterion	Total number of days	Average number of days per year (rate of occurrence)
$\hat{V}_1 \geq 10$ m/s	281	56.2
$\hat{V}_2 \geq 13$ m/s	108	21.6
$\hat{V}_3 \geq 16$ m/s	47	9.4
$\hat{V}_4 \geq 23$ m/s	7	1.4

b. based on mean speeds

Criterion	Total number of days	Average number of days per year (rate of occurrence)
$\bar{V}_1 \geq 5$ m/s	810	162.0
$\bar{V}_2 \geq 7.5$ m/s	277	55.4
$\bar{V}_3 \geq 10$ m/s	96	19.2

4.5 DETERMINATION OF WIND ENVIRONMENT

To determine the street level wind conditions at the intersection of Trade and Tryon Streets in Charlotte, twenty-five measurement locations were used. These are shown within the shaded square in Figure 3.2.

For each of these locations the procedure described above was repeated to determine average rates of occurrence of specific speed intervals. The results are summarized in Tables 4.5 and 4.6, Table 4.5 being based on maximum speed values, Table 4.6 on mean speed values. By using the rates of occurrence in Tables 4.5 and 4.6 with the criteria in section 4.3, Figures 4.2 through 4.5 showing locations of the relevant zones were obtained.

Although recognized as an important factor in human comfort, turbulence intensity ($I_v = \frac{\sigma_v}{\bar{V}} = \frac{R_{r.m.s.}}{R_{mean}}$) is not usually included in comfort criteria except sometimes to specify the range of turbulence intensities in which the criteria apply. Table 4.7 shows the turbulence intensities for each location and wind direction. Appropriate values of $R_{r.m.s.}$ were obtained from Appendix C.

Table 4.5. Total Number of Days and Rate of Occurrence for each Location (based on maximum speeds).

Location	# of days V≥10m/s	rate of occ.	# of days V≥13m/s	rate of occ.	# of days V≥16m/s	rate of occ.	# of days V≥23m/s	rate of occ.
2	50	10.0	10	2.0	2	0.4	-	-
3	134	26.8	31	6.2	11	2.2	-	-
4	322	64.4	106	21.2	37	7.4	4	0.8
5	44	8.8	16	3.2	3	0.6	-	-
6	281	56.2	108	21.6	47	9.4	7	1.4
7	19	3.8	5	1.0	-	-	-	-
9	167	33.4	47	9.4	15	3.0	-	-
10	103	20.6	25	5.0	9	1.8	-	-
12	26	5.2	7	1.4	-	-	-	-
13	267	53.4	102	20.4	36	7.2	6	1.2
14	210	42.0	51	10.2	15	3.0	2	0.4
15	67	13.4	25	5.0	6	1.2	1	0.2
17	154	30.8	44	8.8	15	3.0	2	0.4
18	92	18.4	24	4.8	7	1.4	-	-
19	112	22.4	30	6.0	9	1.8	-	-
20	76	15.2	18	3.6	7	1.4	-	-
23	130	26.0	36	7.2	11	1.44	-	-
24	43	8.6	13	2.6	5	1.0	-	-
25	85	17.0	17	3.4	5	1.0	-	-
30	64	12.8	17	3.4	5	1.0	-	-
31	103	20.6	24	4.8	7	1.4	-	-
33	119	23.8	32	6.4	11	2.2	-	-
34	85	17.0	29	5.8	10	2.0	-	-
39	28	5.6	9	1.8	2	0.4	-	-
40	222	44.4	63	12.6	29	5.8	1	0.2

Table 4.6. Total Number of Days and Rate of Occurrence for each Location (based on mean speeds).

Location	#_of days V>5m/s	rate of occ.	#_of days V>7.5m/s	rate of occ.	#_of days V>10m/s	rate of occ.
2	289	57.8	55	11.0	11	2.2
3	445	89.0	130	26.0	36	7.2
4	955	191.0	321	64.2	103	20.6
5	74	14.8	10	2.0	2	0.4
6	810	162.0	277	55.4	96	19.2
7	39	7.8	5	1.0	-	-
9	598	119.6	142	28.4	41	8.2
10	317	63.4	64	12.8	9	1.8
12	45	9.0	8	1.6	-	-
13	880	176	325	65.0	100	20.0
14	643	128.6	183	36.6	28	5.6
15	218	43.6	55	11.0	7	1.4
17	440	88.0	147	29.4	25	5.0
18	152	30.4	25	5.0	5	1.0
19	405	81.0	48	9.6	10	2.0
20	58	11.6	8	1.6	-	-
23	417	83.4	132	26.4	32	6.4
24	133	26.6	15	3.0	4	0.8
25	274	54.8	58	11.6	12	2.4
30	252	50.4	37	7.4	9	1.8
31	353	70.6	67	13.4	14	2.8
33	232	46.4	34	6.8	6	1.2
34	212	43.4	46	9.2	10	2.0
39	90	18.0	20	4.0	4	0.8
40	422	84.4	135	27.0	44	8.8

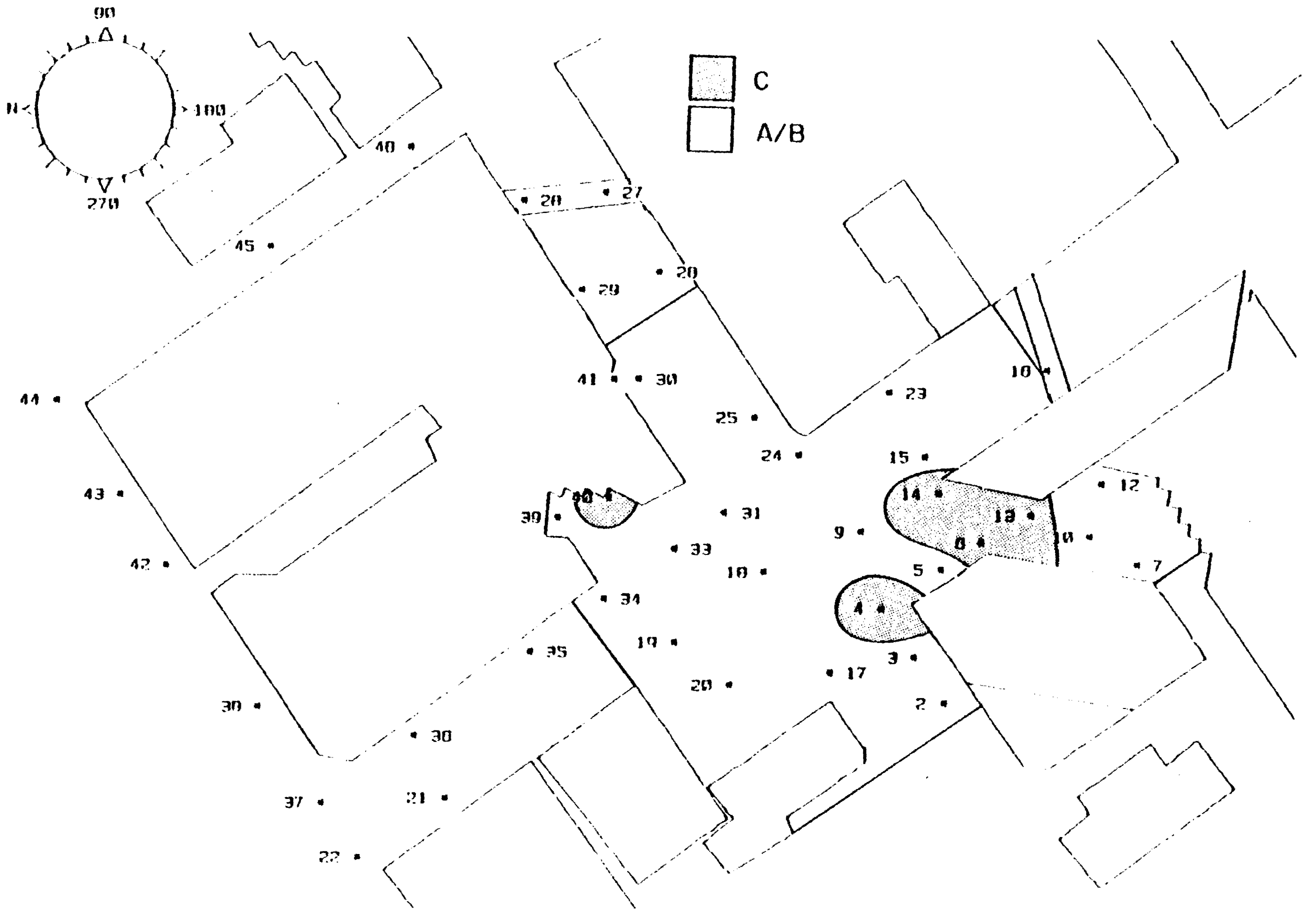


Figure 4.2 Murakami Criteria

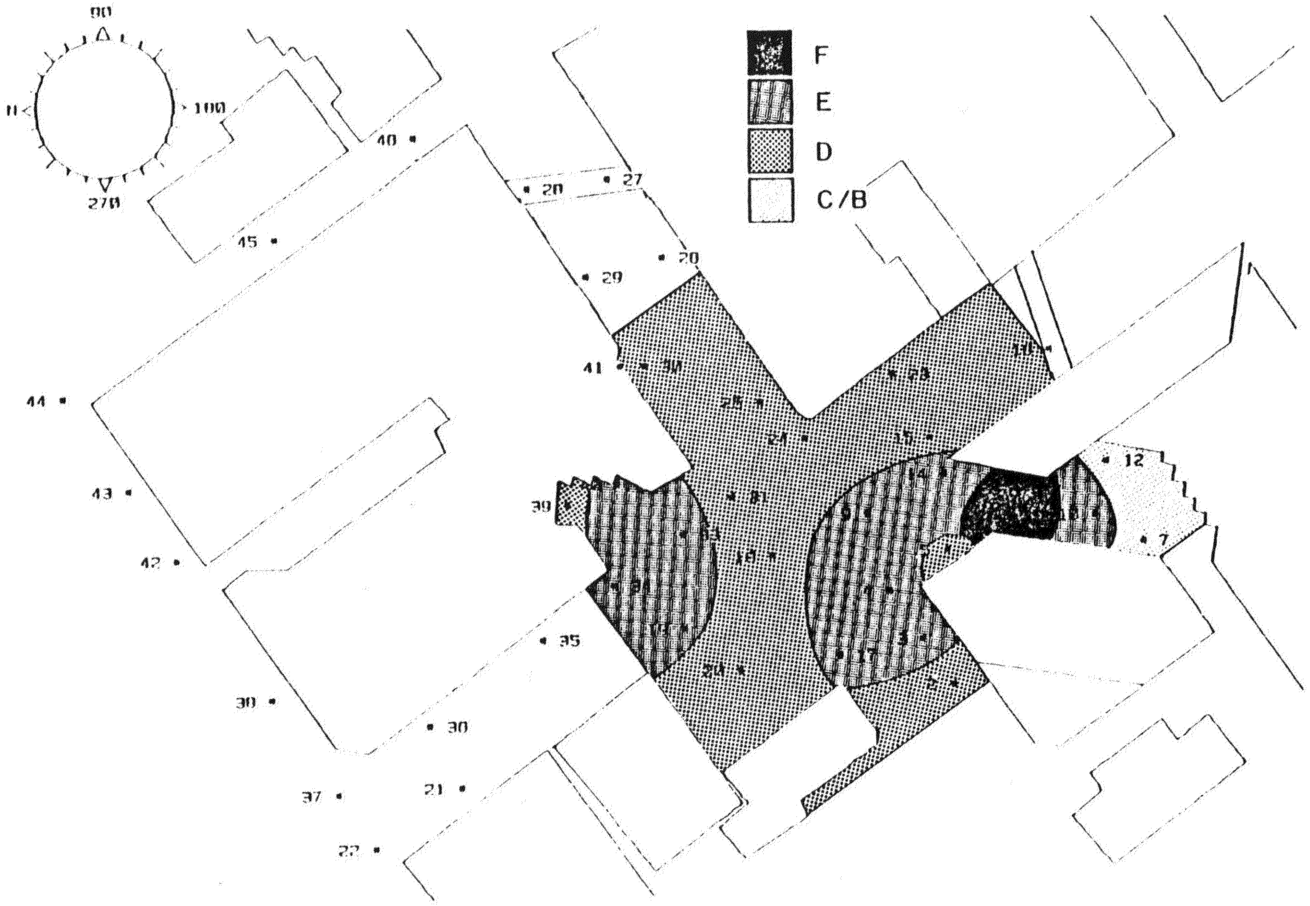


Figure 4.3 Melbourne Criteria

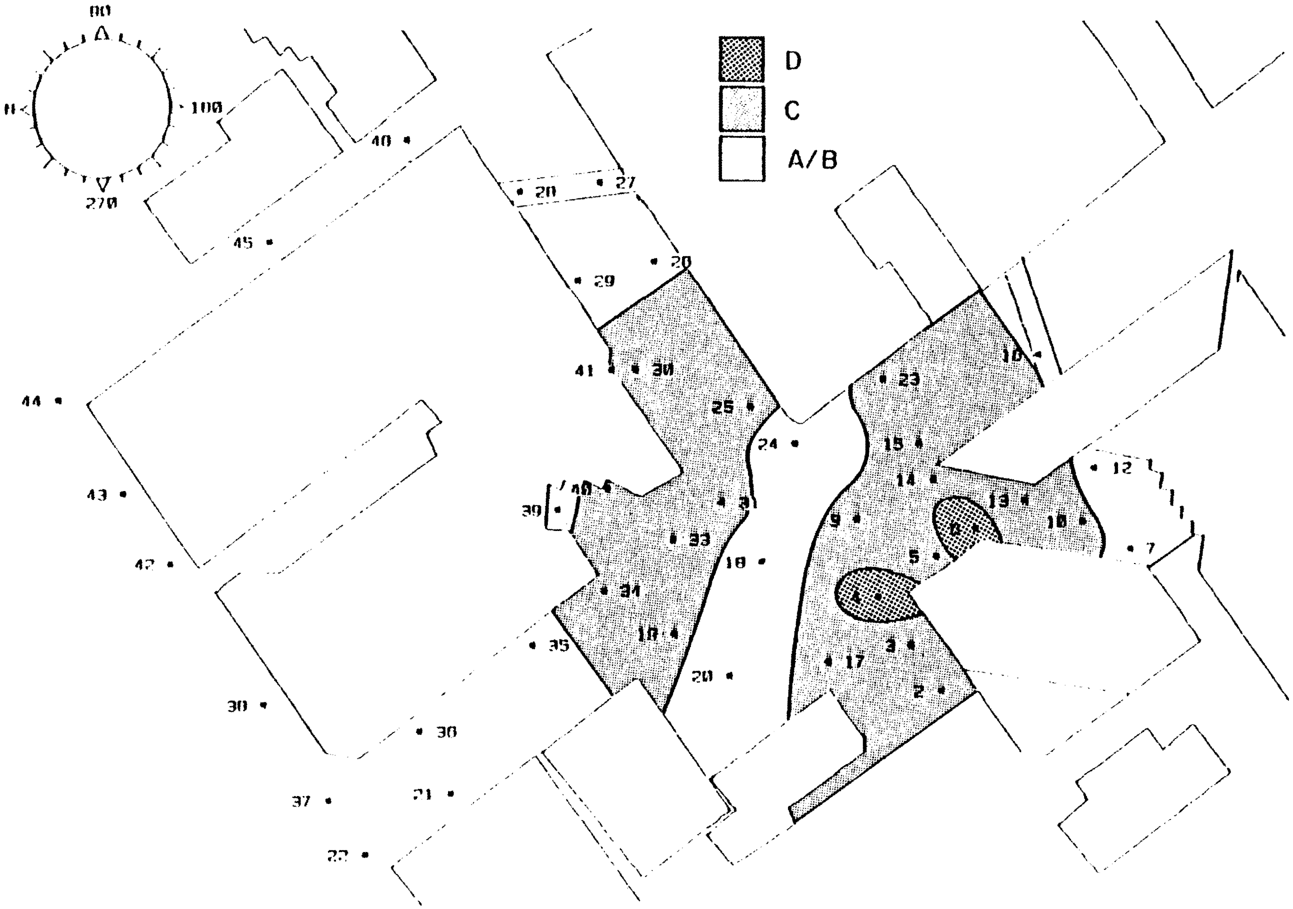


Figure 4.4 Davenport Criteria

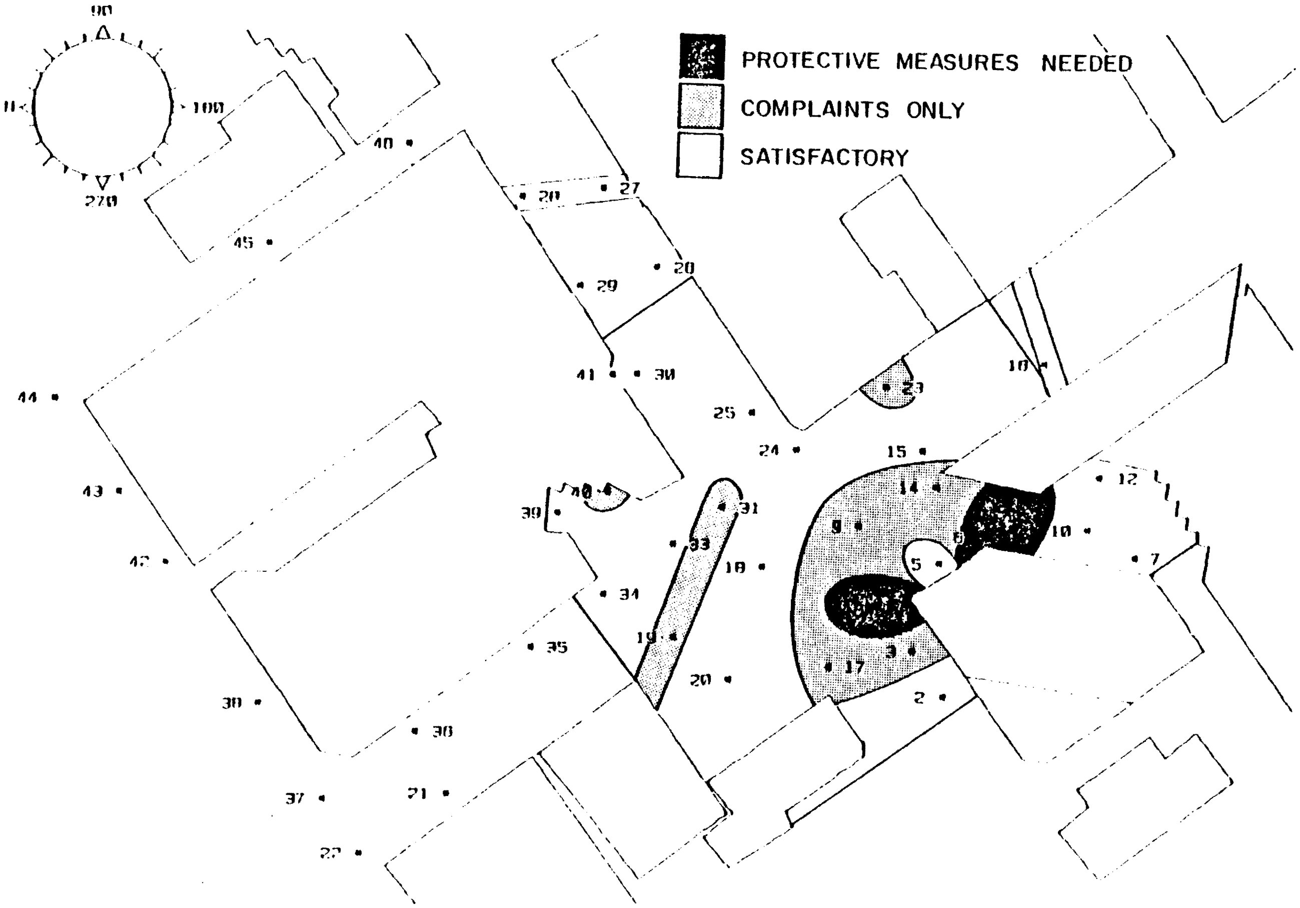


Figure 4.5 Penwarden Criteria

Table 4.7. Turbulence Intensities, I_v, (%).

Location	Wind Direction							
	N	NE	E	SE	S	SW	W	NW
2	10	120	277	145	64	10	10	43
3	21	153	124	30	30	10	7	15
4	13	10	12	10	23	10	6	9
5	25	22	22	28	90	112	32	43
6	22	21	15	9	8	11	39	42
7	37	82	19	20	35	26	43	39
9	16	11	12	16	10	21	8	12
10	14	25	27	12	11	15	106	57
12	63	55	18	20	18	25	74	35
13	11	14	42	10	9	9	46	14
14	15	14	13	20	14	15	56	15
15	100	17	16	62	40	12	34	20
17	13	19	32	14	22	17	17	56
18	68	20	9	15	33	36	50	24
19	32	11	15	15	27	25	24	26
20	13	36	37	37	76	185	40	82
23	36	14	14	28	99	11	12	11
24	37	16	24	28	166	19	34	35
25	40	170	20	14	262	15	19	11
30	95	32	14	14	35	17	14	30
31	15	50	18	10	30	18	15	11
33	25	18	8	10	23	39	17	20
34	24	313	16	14	30	21	26	21
39	18	30	133	26	56	98	111	243
40	22	26	8	8	23	37	16	15

Chapter V

DISCUSSION OF RESULTS

Before discussing the results in detail, it is worth recalling the assumptions that were made to combine the meteorological data with the wind tunnel measurements.

1. The velocity profile at the airport could be represented by a power law appropriate to open country.
2. The fastest mile wind speed could be converted to a mean hourly wind speed by multiplication by a constant factor.
3. A mean hourly wind speed at the airport could be converted to a mean hourly wind speed in the approach flow to the city via the gradient wind speed.

These assumptions are frequently used in the analysis of wind data but their use is open to debate and errors introduced here would clearly affect the applicability of the criteria. However, for purposes of comparing the pedestrian comfort criteria, it should be noted that the errors would be common to all of them.

Further assumptions had to be made to convert the published criteria into a form compatible with the meteorological data. Murakami's criteria could be applied directly.

In Melbourne's case, it was assumed that two occurrences per year were equivalent to one occurrence in daylight hours per year and that a wind speed would only exceed a specified value once per day. This could have underestimated the number of occurrences. Davenport and Penwarden expressed their criteria in terms of percentage of time on the basis of mean hourly wind speed. In converting this percentage to days per year, it was assumed that if the mean hourly speed on a given day, based on fastest mile wind speed, exceeded the criterion speed, then the whole day could be considered as the period in which the criterion was exceeded. This assumption might have overestimated the exceedance time. It was assumed that winds were equally likely to occur at night or during the day.

Considering Figures 4.2 through Figure 4.5, the following conclusions can be drawn:

a. According to Murakami, Figure 4.2 suggests that all the areas under consideration are suitable for strolling, and all except the areas which include locations 4, 6, 13, 14, and 40 are suitable for both short or long exposure, i.e., the whole city center is quite satisfactory from a pedestrian comfort point of view.

b. Figure 4.3, based on Melbourn's criteria, indicates that the area around locations 6 and 13 is dangerous. The area which includes locations 3, 4, 9, 10, 14, and 17, and that which includes locations 19, 33, 34, and 40, are all unacceptable but not dangerous. The rest of the area under consideration could be used for walking except in the sheltered area near locations 7 and 12 which could be suitable for short exposure activities.

c. Davenport's criteria (Figure 4.4) suggests that the areas near locations 4 and 6 are suitable for walking only, while that near locations 18, 20, and 24 is suitable for both long or short exposure. The rest of the area would be considered suitable for strolling.

d. Figure 4.5 which represents Penwarden's criteria indicates that the areas around locations 4, 6, and 13 are extremely unsatisfactory and would not be acceptable without modification. The areas around locations 3, 9, 14, 17, 19, 28, 31, and 40 would be unsatisfactory, and the rest of the area would be considered satisfactory.

e. Generally, by comparing Figures 4.2 through Figure 4.5, it can be seen that Melbourne's recommendations are the most severe while Murakami's are the least severe. It can be seen, also, that Melbourne and Penwarden are very much in agreement, whereas Davenport's recommendations lie somewhere in between Murakami's and that of Melbourne and Penwarden.

It is clear from the above conclusions that the area between Radisson Hotel and the North Carolina National Bank (locations 6 and 13), the area near location 4 on the corner of the North Carolina National Bank, and the area on the corner of the Independence Center (location 40) are the windiest spots. The severity of the conditions depends upon the criteria chosen.

In order to judge the applicability of the criteria, it is interesting to consider what is known about the nature of the area. The area between the North Carolina National Bank and the Radisson Hotel is known to be windy, especially in winter. Even in summer when conditions are very still, a breeze can be felt in that area which could be advantageous when it is hot and humid. However, modifications have had to be made to the doors in that area including provision for shutting off the passage way beyond location 7 on windy days. In addition, a vertical bronze disk of 2 m diameter is located between locations 9 and 5. This disk was supposed to rotate slowly about a vertical axis in the wind. When this disk was first installed, it rotated so fast that governors had to be added to slow it down to a safe speed.

Although conditions may not be as severe as suggested by Melbourne or Penwarden, they are certainly more severe than indicated by Murakami. It is unfortunate that Murakami's criteria do not seem to agree with known conditions since they are in the right form for the application of daily fastest mile records. One problem with Murakami's criterion which might be the reason for its poor agreement with known conditions, is that it sets a certain speed and then varies the rate of occurrence depending on the activity whereas Melbourne and Davenport set the rate of occurrence and vary the criterion speed. However, Penwarden also uses a fixed speed and variable rate of occurrence, but his speeds are averaged over a long time period.

It is interesting to find out why the areas around locations 4, 6, 13, and 40 have the windiest conditions. By searching the meteorological records for the five year period, the following facts were obtained.

1. At location 4 the peak wind speed exceeded 23 m/s
   twice for S.W. winds, and
   twice for N.W. winds,
   whereas it exceeded 16 m/s
   one time for E. winds,
   twice for S.E. winds,

12 times for S.W. winds,
6 times for W. winds, and
16 times for N.W. winds.

2. At location 6 the peak wind speed exceeded 23 m/s
    one time for S.E. winds, and
    6 times for S.W. winds,

    whereas it exceeded 16 m/s
    one time for E. winds,
    10 times for S.E. winds,
    4 times for S. winds,
    31 times for S.W. winds, and
    one time for W. winds.

3. At location 13 the peak wind speed exceeded 23 m/s 6 times for S.W. winds, whereas it exceeded 16 m/s
    31 times for S.W. winds, and
    5 times for N.W. winds.

4. At location 40 the peak wind speed exceeded 16 m/s
    twice for E. winds,
    7 times for S.E. winds,
    7 times for S.W. winds,
    one time for W. winds, and
    12 times for N.W. winds.

    It exceeded 23 m/s only once when the wind was from the N.W.

From the above facts, the following conclusions can be drawn:

a. The windy conditions in the area around location 4 are due to the sharp corner which exists on the North Carolina National Bank where the flow accelerates around that corner and causes windy conditions.

b. For areas around locations 6 and 13 S.W. winds driven through the narrow opening between the Radisson Hotel and the North Carolina National Bank create very high wind speeds.

c. The area around location 40 lies under an overhanging corner which has a height of between 2 to 3 stories. Here the flow is channelled under the corner when the wind is from either an easterly or westerly direction.

It is interesting to note that the windy conditions are due mainly to funnelling effects. The wind tunnel results showed very high speed ratios at location 6 when the wind was from the east, presumably due to wind being driven down the face of the North Carolina National Bank building. However, apparently strong winds from that direction are rare and the greatest wind speeds at 6 are likely to occur due to a funnelling effect when the wind is from the S.W.

In the previous analysis and discussion the acceptability of wind environment conditions was based on speed criteria (maximum or mean) and not on gustiness. It is known that gustiness is important in human response to windy conditions although it is not usually included in the acceptability criteria except to specify the range of applicability of the criteria. However, it is reasonable sometimes to make assumptions about the turbulence intensity in order to convert mean wind speeds to peaks or vice-versa (as illustrated in Chapter II). The most common assumption is that the turbulence intensity ranges from 15% to 30%. In this investigation, many locations would agree with this assumption (see Table 4.7); but there were locations where the turbulence intensity was over 100% and in one case over 300%, often these locations had low mean speeds but had peak/mean speed ratios as high as 6. Clearly, a standard conversion from mean to peak as described in Chapter II, on the assumption of, say, 15% turbulence intensity, would be highly misleading in these cases.

Chapter VI

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that even when a wind tunnel investigation has been made of an arrangement of buildings, the interpretation of the results in terms of pedestrian comfort can vary considerably. In this case, it is clear that an inappropriate arrangement of buildings, creating a funnel, has caused a problem, but a judgement of the severity of the problem would depend very much on the design criteria used as well as the procedure used for the transfer of wind data from the airport to the city.

It is recommended that further research be conducted in which actual wind conditions in the city are related to conditions at the airport. In this way the suitability of the wind speed conversion and design criteria can be tested.

It would also be useful if design criteria could be developed in a suitable form for the application of meteorological data. Since daily fastest mile wind speeds are readily available in the U.S.A., criteria of the type that specifies the number of days per year that a given wind speed is exceeded would be very suitable.

REFERENCES

1. Isyumov, N. and A. G. Davenport. 1975. The Ground Level Wind Environment in Built-Up Areas, Proceedings of the 4th International Conference on Wind Effects on Buildings and Structures, Heathrow.

2. Aynsley, R. M., W. H. Melbourne and B. J. Vickery. 1977. Architectural Aerodynamics, Applied Science Publishers, London.

3. Arens, E. A. 1981. Designing for an Acceptable Wind Environment, Transportation Engineering Journal, ASCE, Vol. 107, No. TE2, March. pp. 127-141.

4. Murakami, S. 1982. Wind Tunnel Modeling Applied to Pedestrian Comfort, Proceedings of the International Workshop on Wind Tunnel Modeling Criteria and Techniques in Wind Engineering Applications, Gaithersburg, Maryland.

5. Irwin, H.P.A.H. 1981. A Simple Omnidirectional Sensor for Wind-Tunnel Studies of Pedestrian-Level Winds, Journal of Wind Engineering and Industrial Aerodynamics, 7:219-239.

6. Sparks, P. R., T. A. Reinhold, and F. J. Maher. 1982. A Study of the Wind Effects on Independence Center, Charlotte, North Carolina, College of Engineering. VPI-E-82-1, January.

7. Reinhold, T. A., H. W. Tieleman, and F. J. Maher. 1978. Simulation of the Urban Neutral Boundary Layer for the Model Study of Wind Loads on Tall Buildings, College of Engineering, VPI-E-77-12, March.

8. American National Standards Institute. 1981. Building Code Requirements for Minimum Design Loads on Buildings and Other Structures, A58.1 - draft revision.

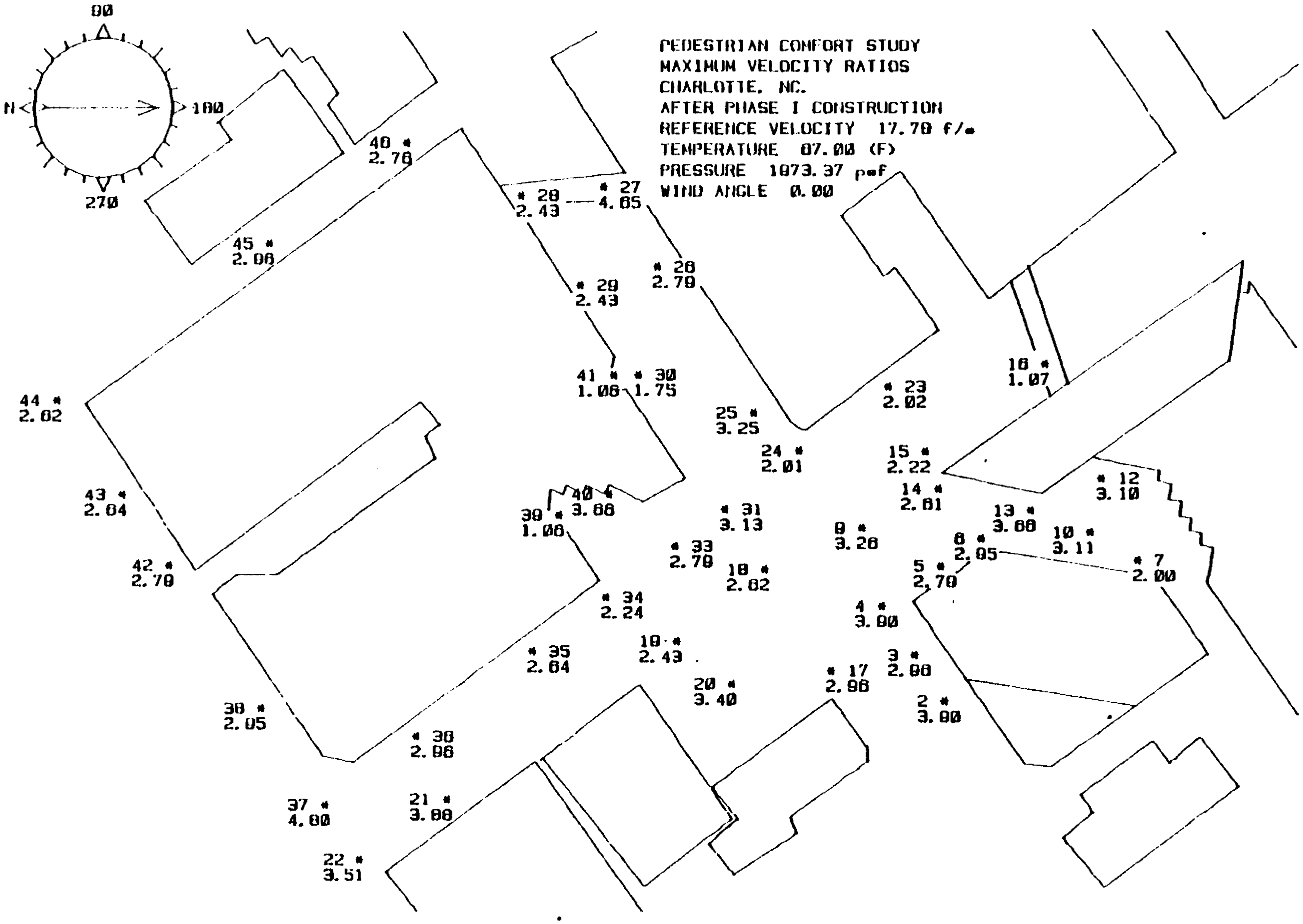
9. Durst, C. S. 1960. Wind Speeds Over Short Periods of Time, Meteor. Mag., 89:181-186.

APPENDICES

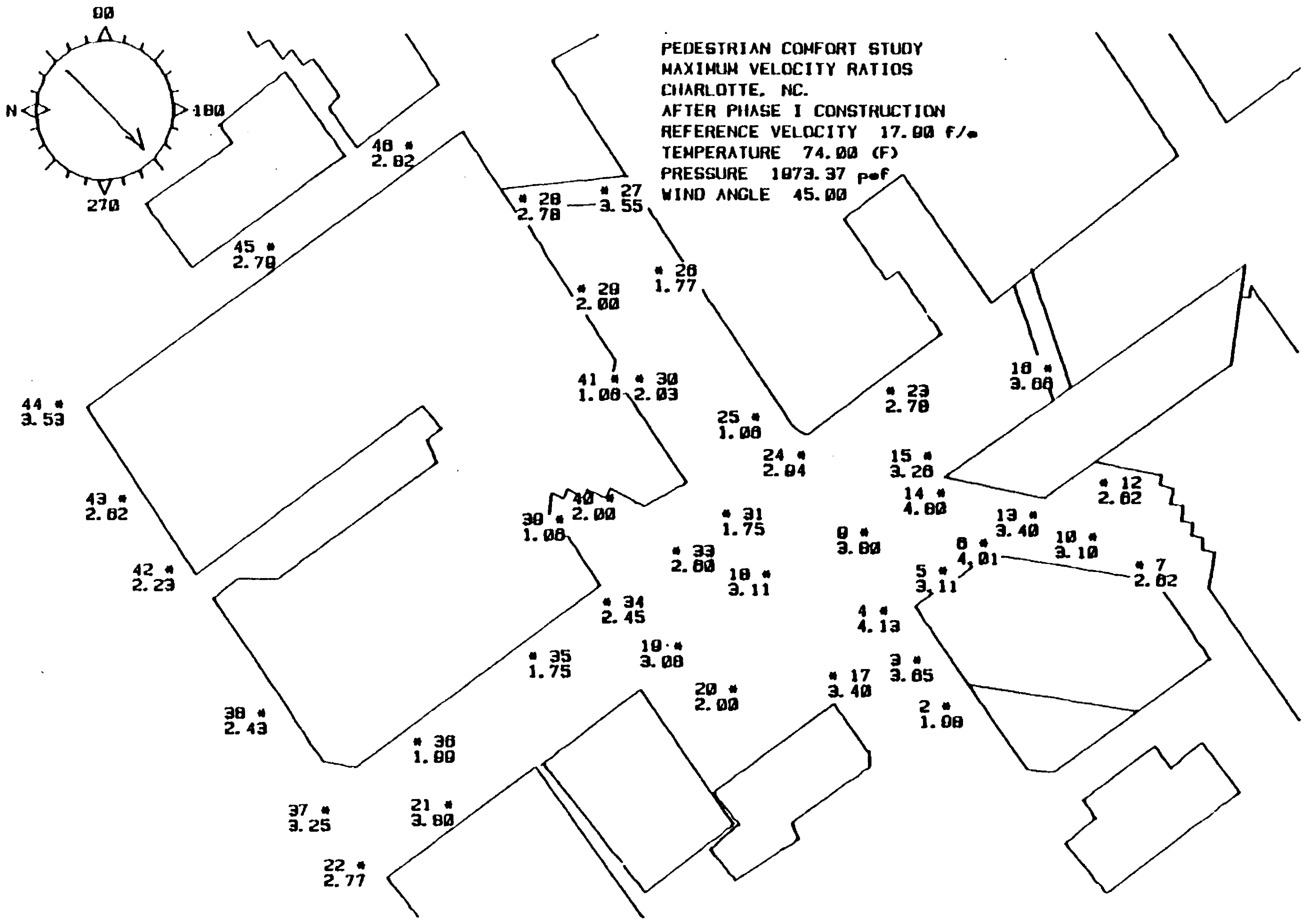
The following plots show the locations of the sensors and the corresponding velocity (speed) ratios for appropriate wind directions. References to the phase of construction, reference velocity, temperature and pressure refer to the model layout and conditions under which the wind tunnel tests were conducted.

APPENDIX A

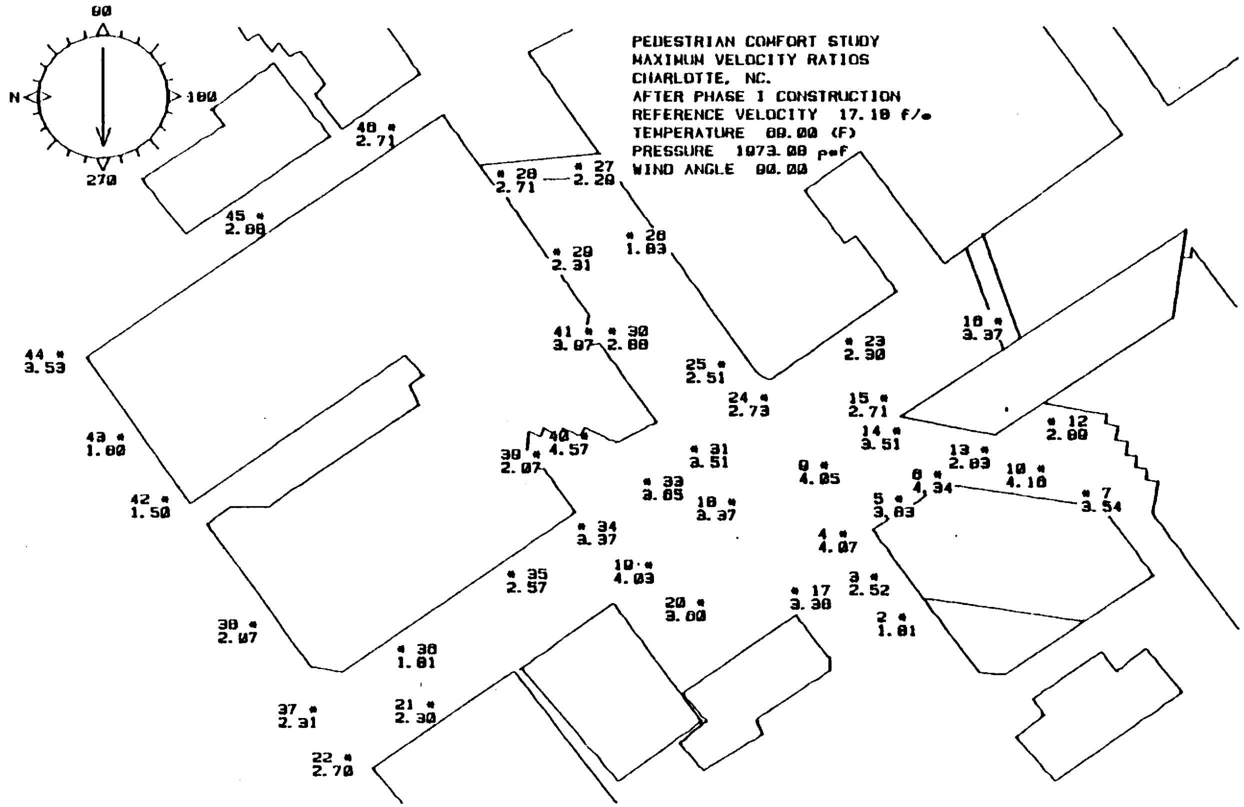
MAXIMUM VELOCITY (SPEED) RATIOS



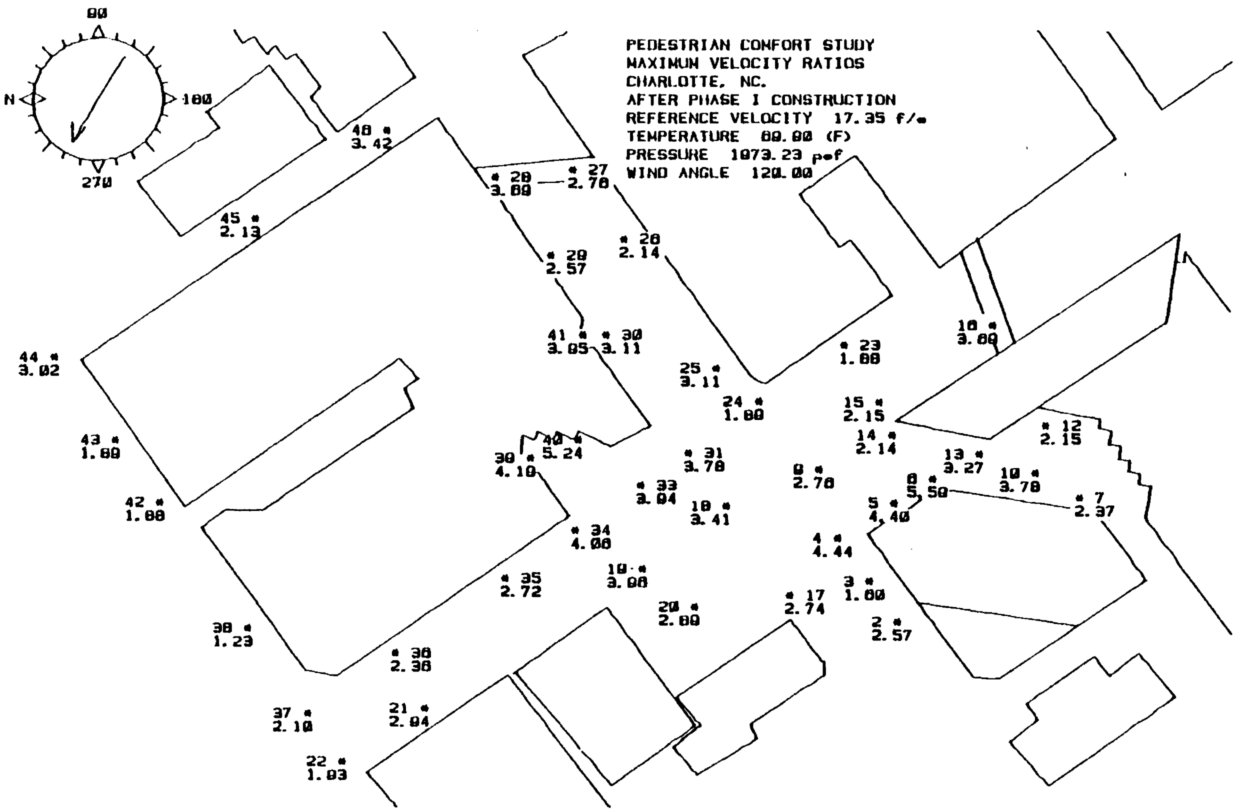
PEDESTRIAN CONFORT STUDY
MAXIMUM VELOCITY RATIOS
CHARLOTTE. NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.70 f/s
TEMPERATURE 67.00 (F)
PRESSURE 1073.37 psf
WIND ANGLE 0.00



PEDESTRIAN COMFORT STUDY
MAXIMUM VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.00 f/s
TEMPERATURE 74.00 (F)
PRESSURE 1073.37 psf
WIND ANGLE 45.00

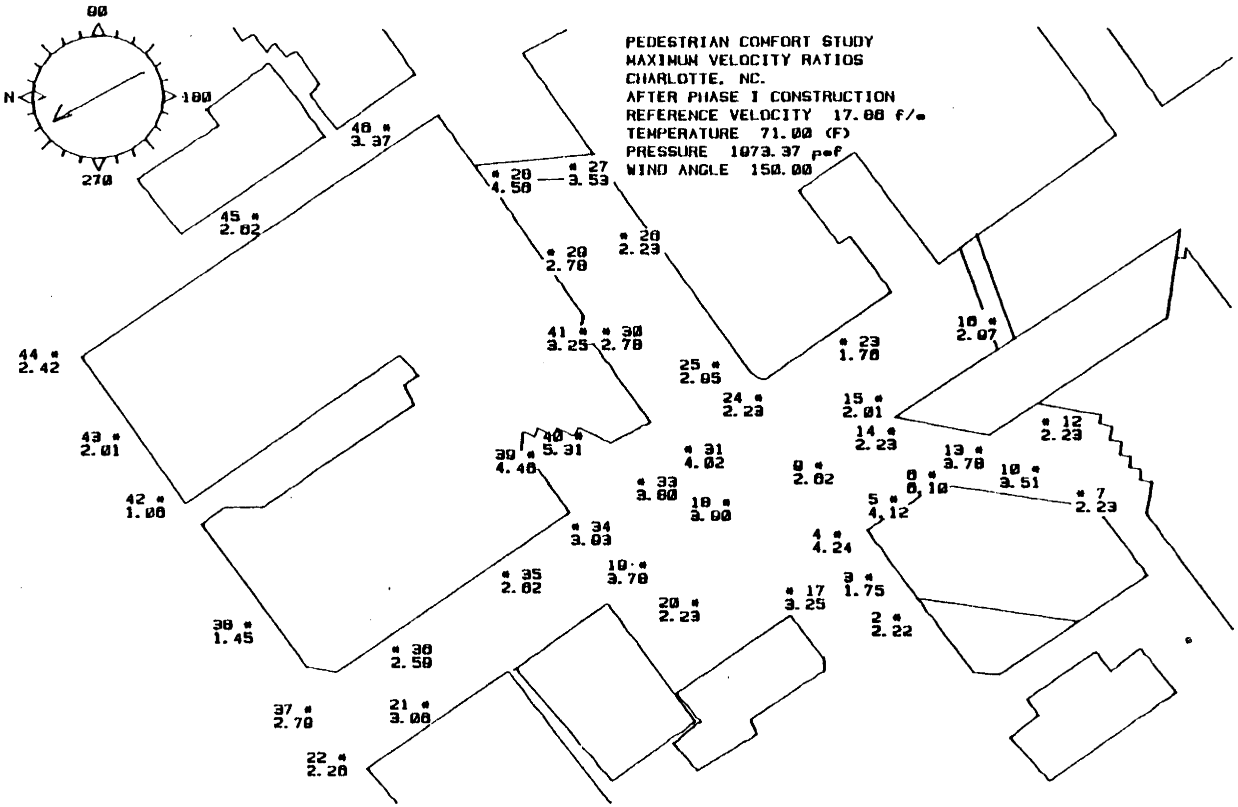


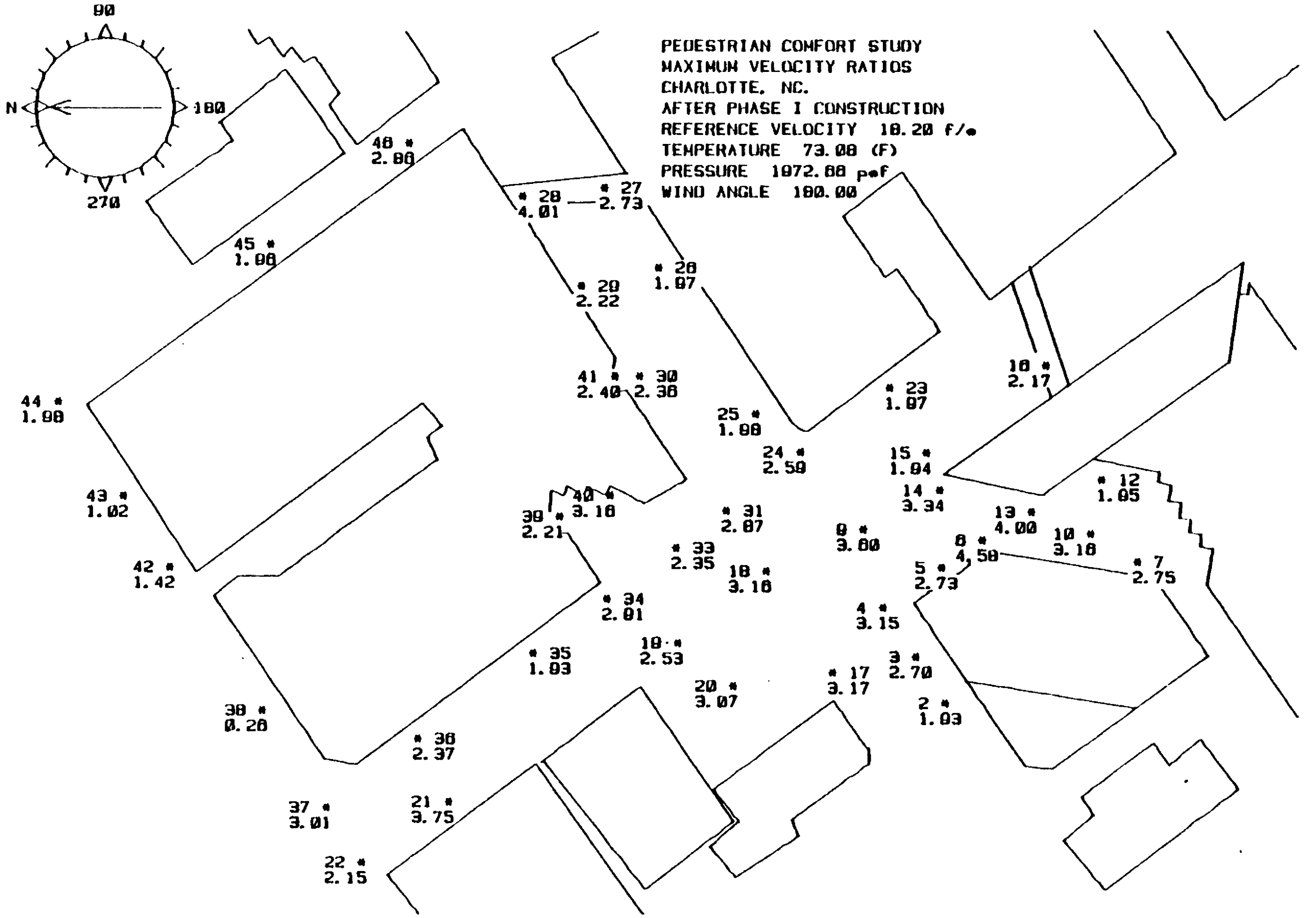
PEDESTRIAN COMFORT STUDY
MAXIMUM VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.10 f/s
TEMPERATURE 88.00 (F)
PRESSURE 1973.00 psf
WIND ANGLE 90.00



PEDESTRIAN CONFORT STUDY
MAXIMUN VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.35 f/s
TEMPERATURE 60.00 (F)
PRESSURE 1073.23 psf
WIND ANGLE 120.00

PEDESTRIAN COMFORT STUDY
MAXIMUM VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.88 f/s
TEMPERATURE 71.00 (F)
PRESSURE 1973.37 psf
WIND ANGLE 150.00





PEDESTRIAN COMFORT STUDY
MAXIMUM VELOCITY RATIOS
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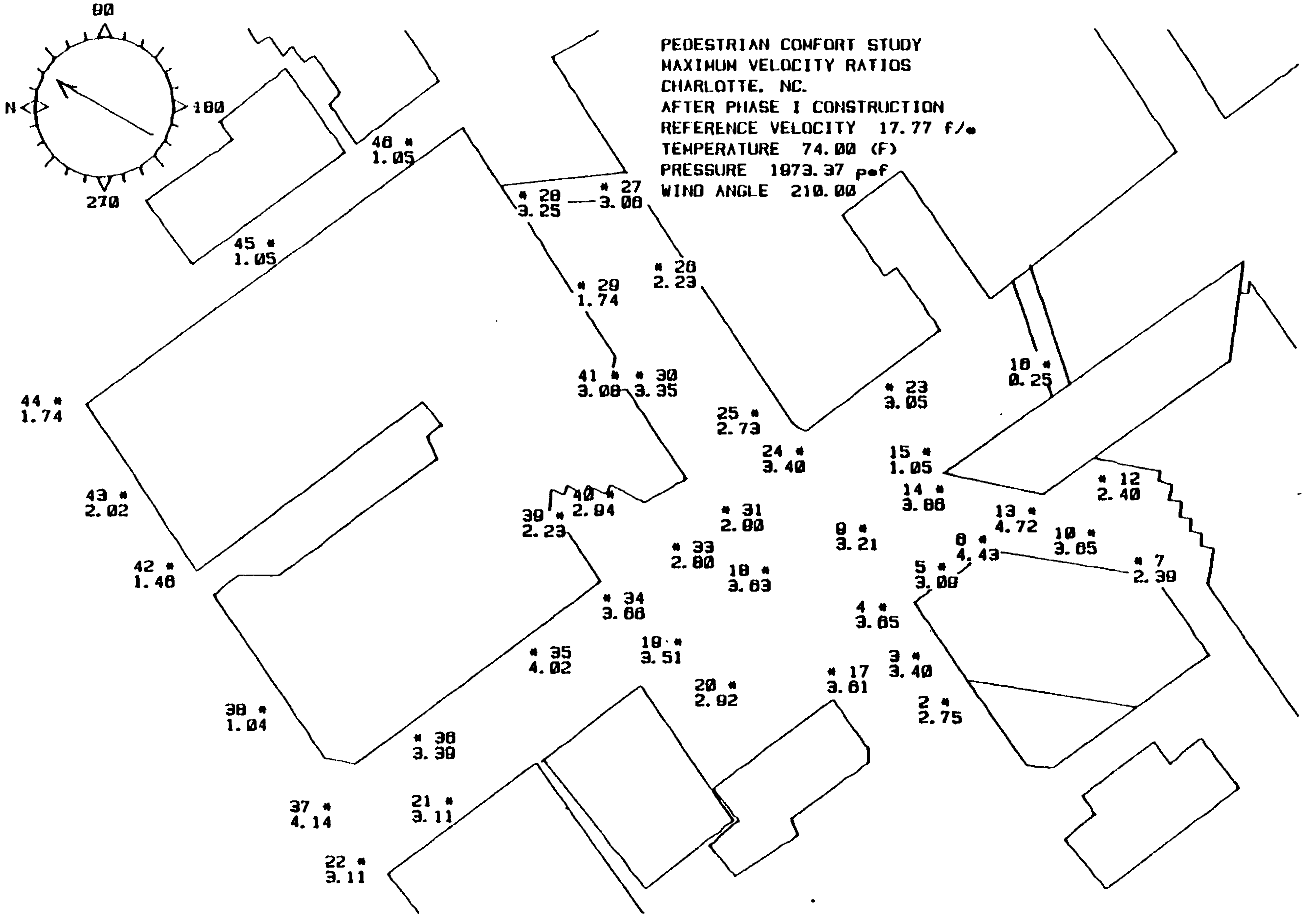
PRESSURE 1972.00 psf
WIND ANGLE 180.00



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MAXIMUM VELOCITY RATIOS
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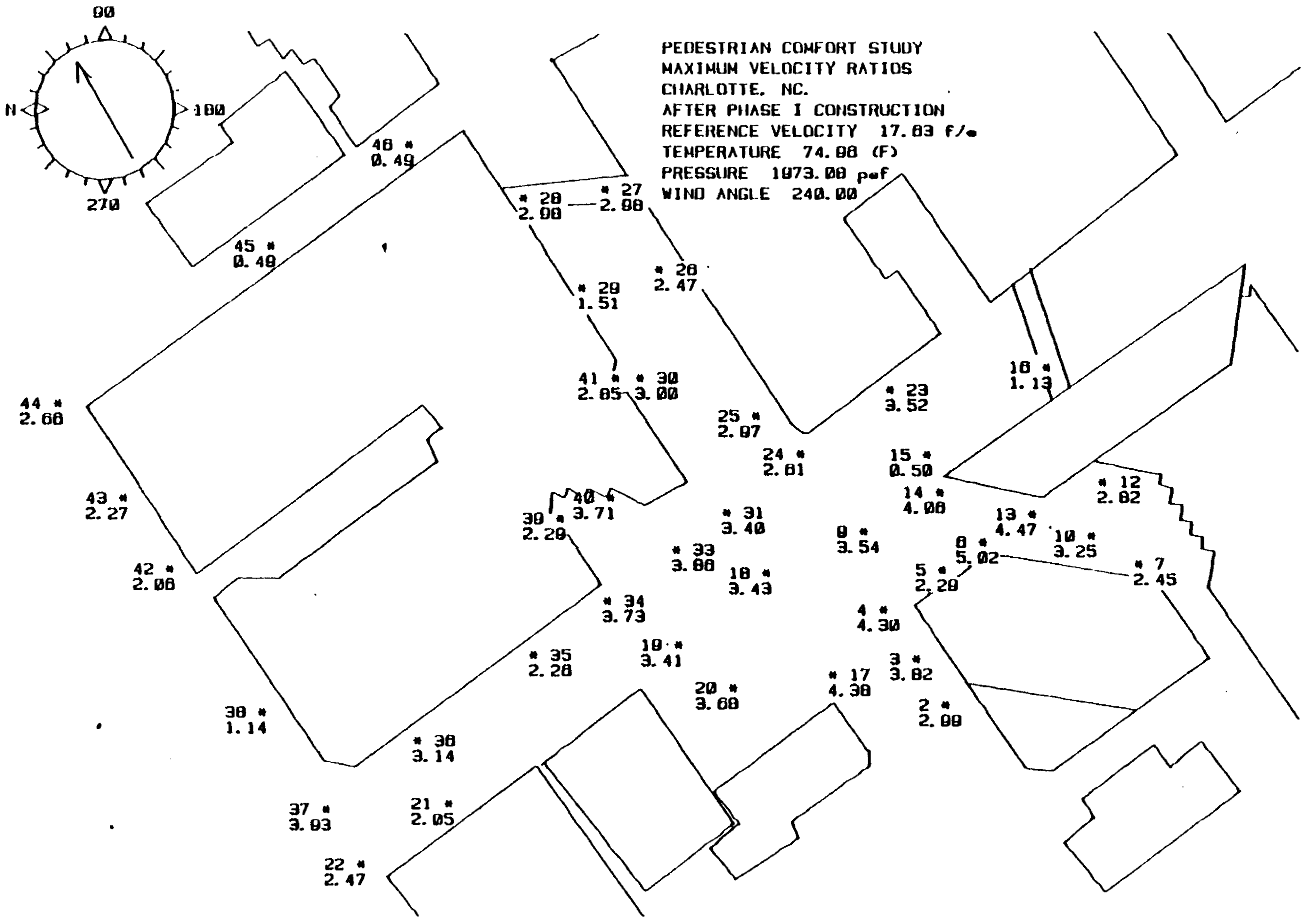
WIND ANGLE 210.00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MAXIMUM VELOCITY RATIOS
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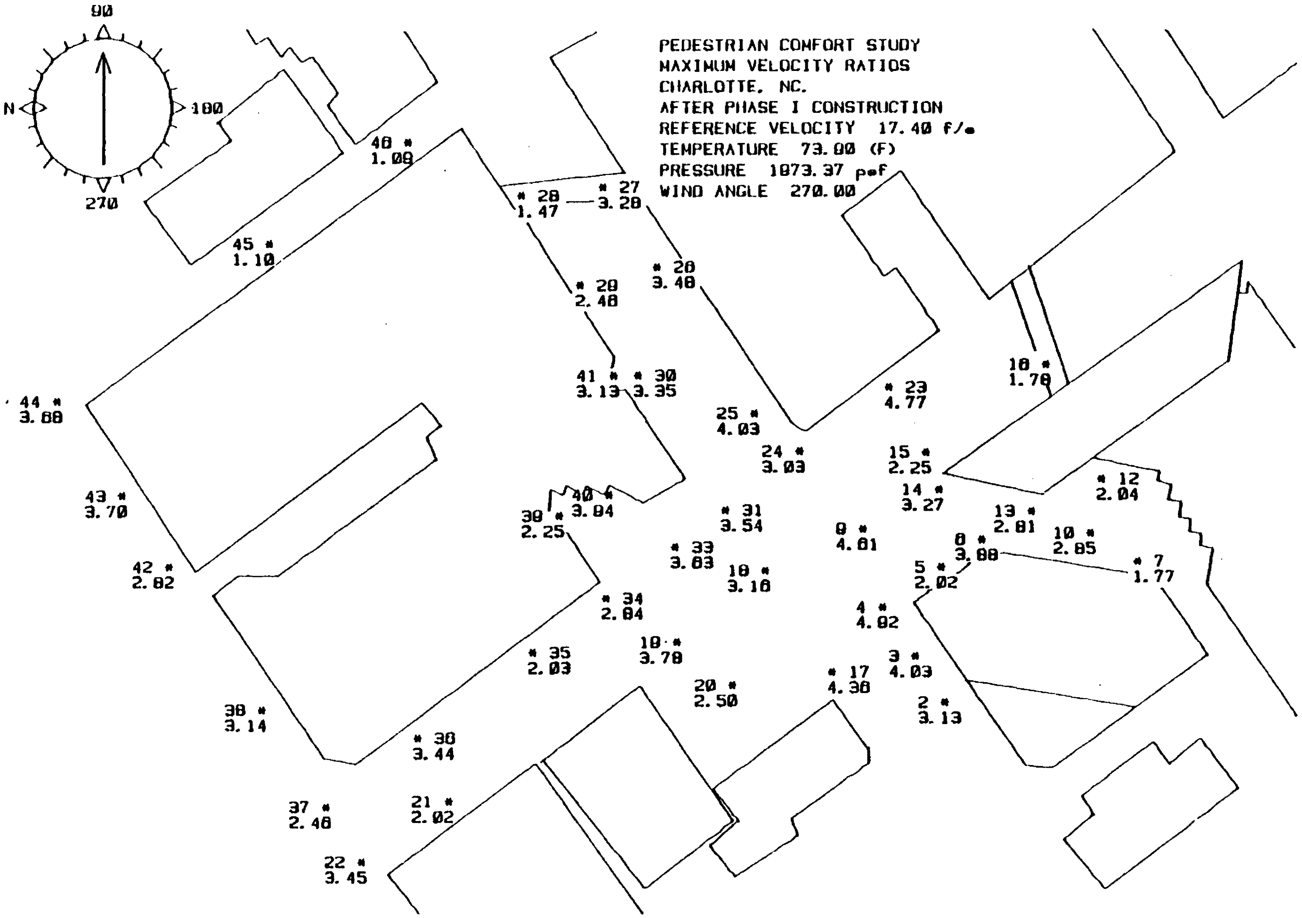
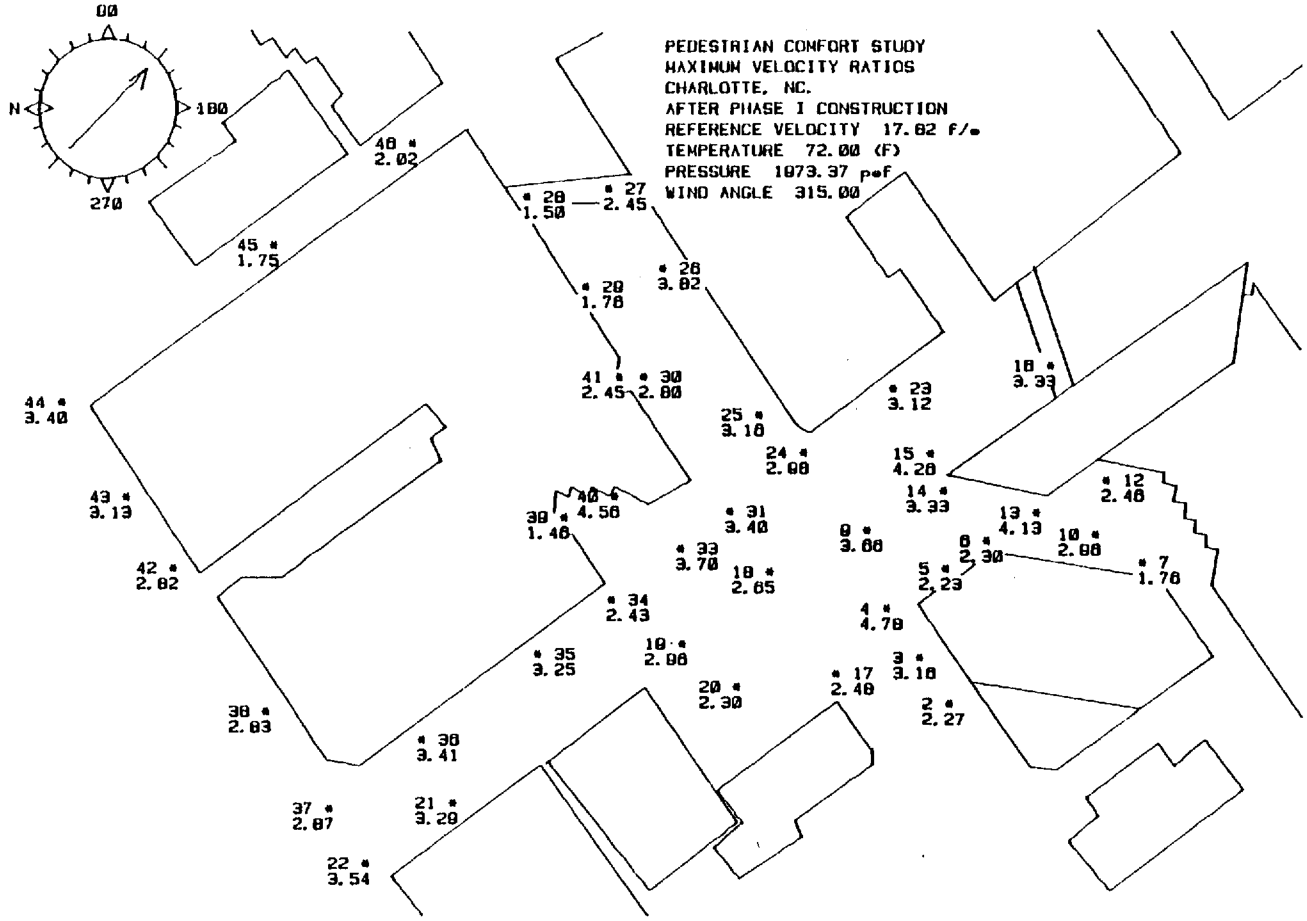
PRESSURE 1073.00 psf
WIND ANGLE 240.00



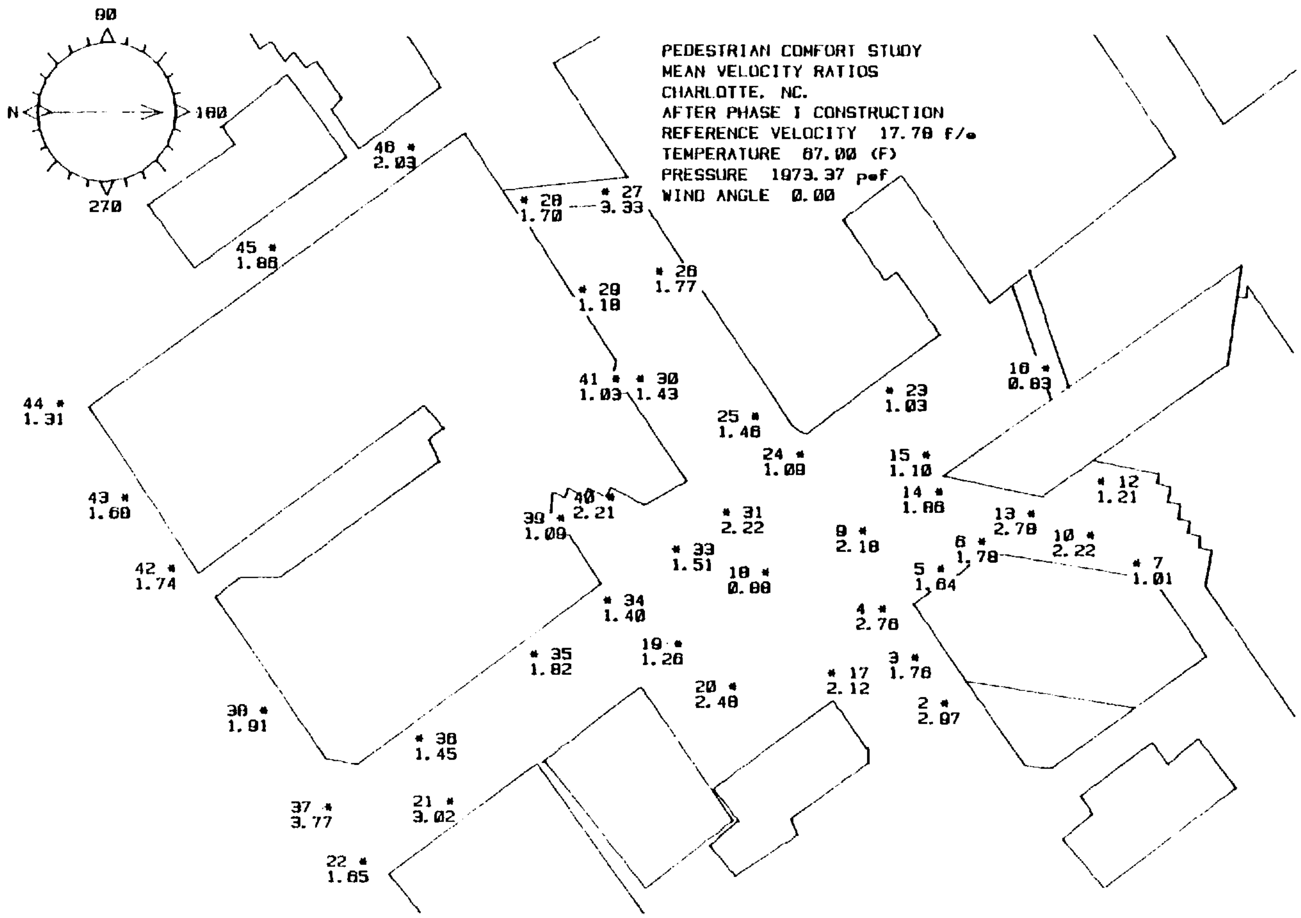
PEDESTRIAN COMFORT STUDY
MAXIMUM VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.40 f/s
TEMPERATURE 73.00 (F)
PRESSURE 1873.37 psf
WIND ANGLE 270.00



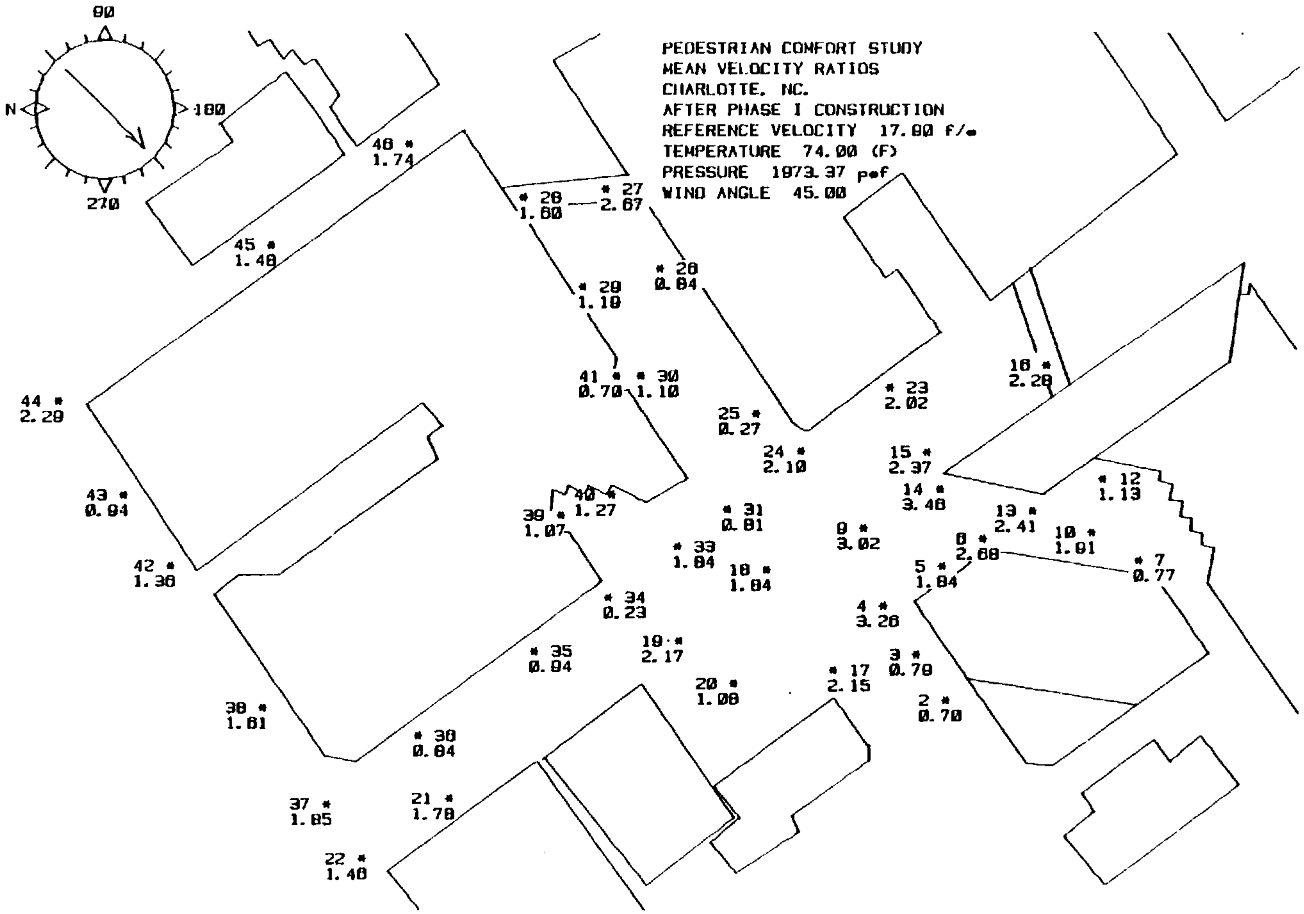
PEDESTRIAN COMFORT STUDY
MAXIMUM VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.82 f/s
TEMPERATURE 72.00 (F)
PRESSURE 1073.37 psf
WIND ANGLE 315.00

APPENDIX B

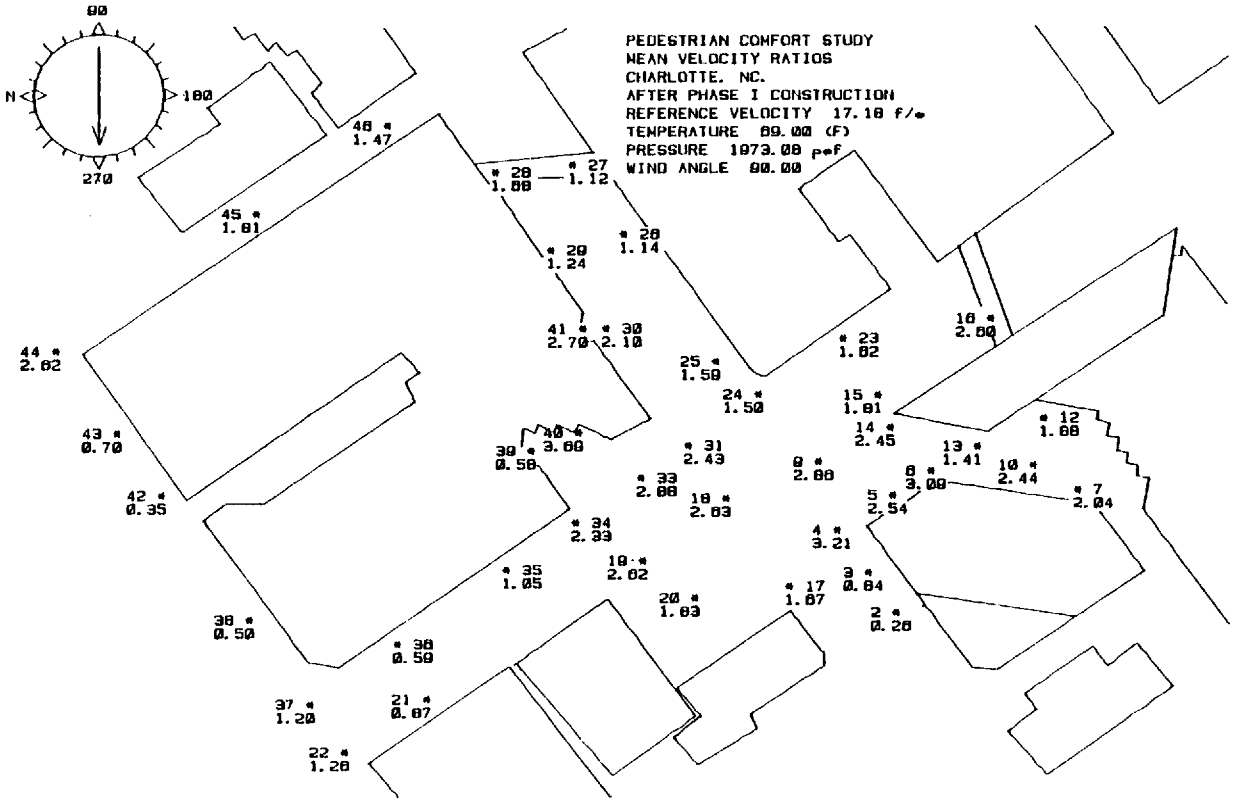
MEAN VELOCITY (SPEED) RATIOS



PEDESTRIAN COMFORT STUDY
MEAN VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.78 f/s
TEMPERATURE 67.00 (F)
PRESSURE 1973.37 psf
WIND ANGLE 0.00



PEDESTRIAN COMFORT STUDY
MEAN VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.80 f/s
TEMPERATURE 74.00 (F)
PRESSURE 1973.37 psf
WIND ANGLE 45.00



PEDESTRIAN COMFORT STUDY
MEAN VELOCITY RATIOS
CHARLOTTE. NC.
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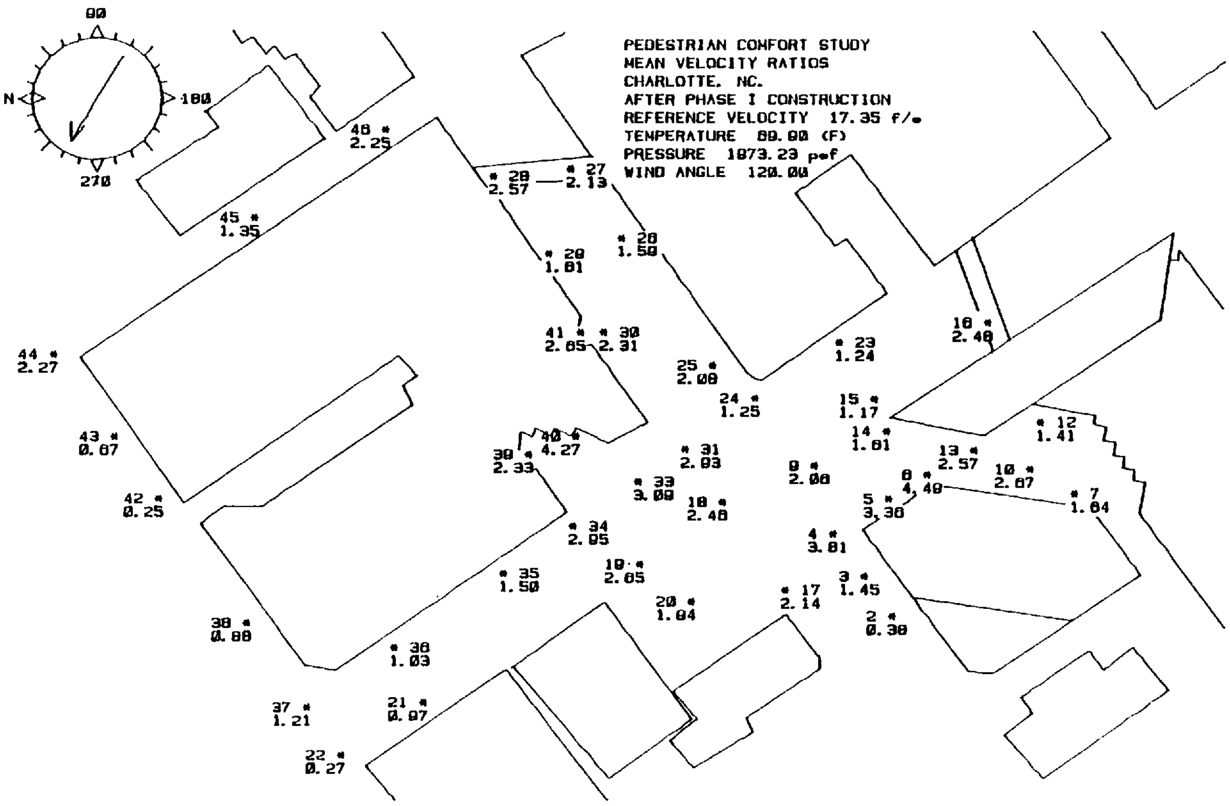
PRESSURE 1873.88 psf
WIND ANGLE 90.00



PEDESTRIAN COMFORT STUDY
MEAN VELOCITY RATIOS
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TEMPERATURE 69.00 (F)
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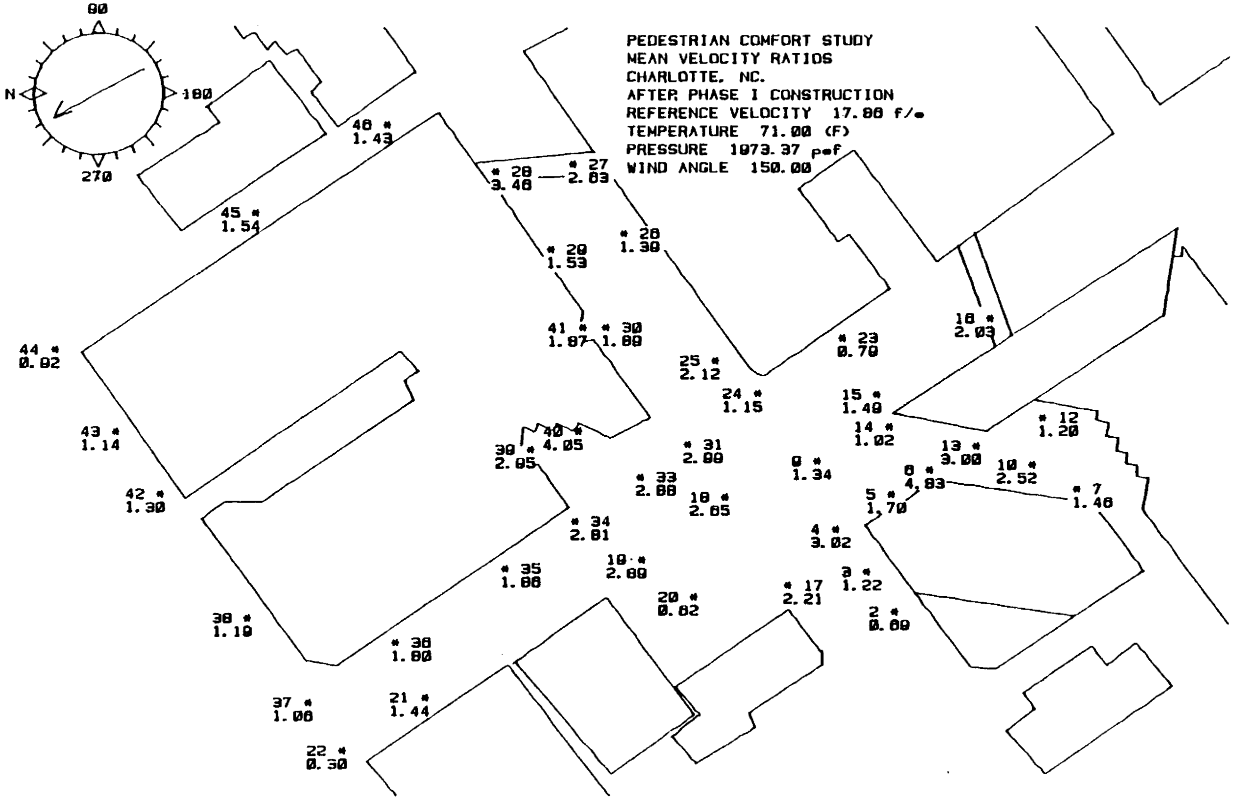
WIND ANGLE 120.00



PEDESTRIAN COMFORT STUDY
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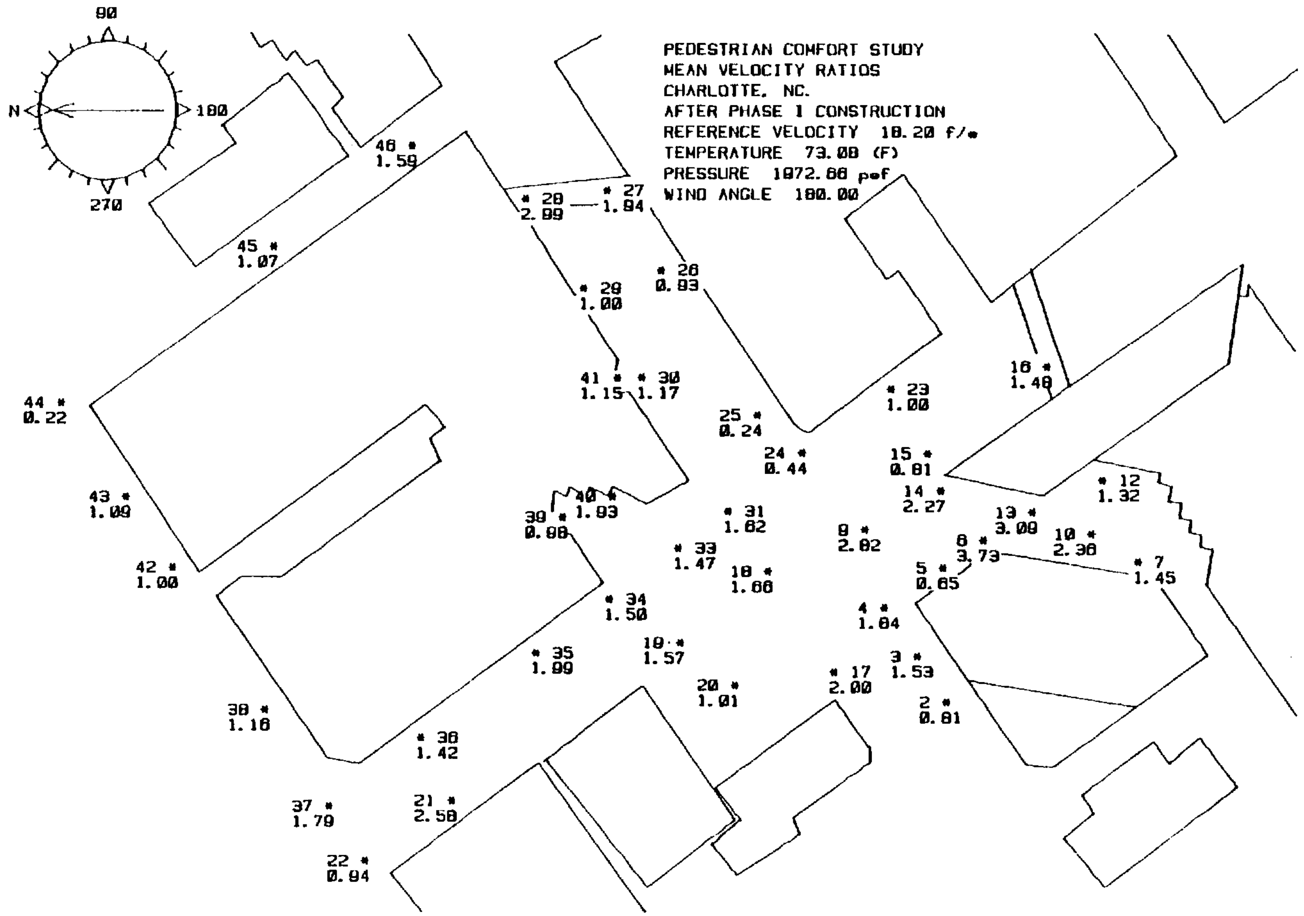
WIND ANGLE 150.00



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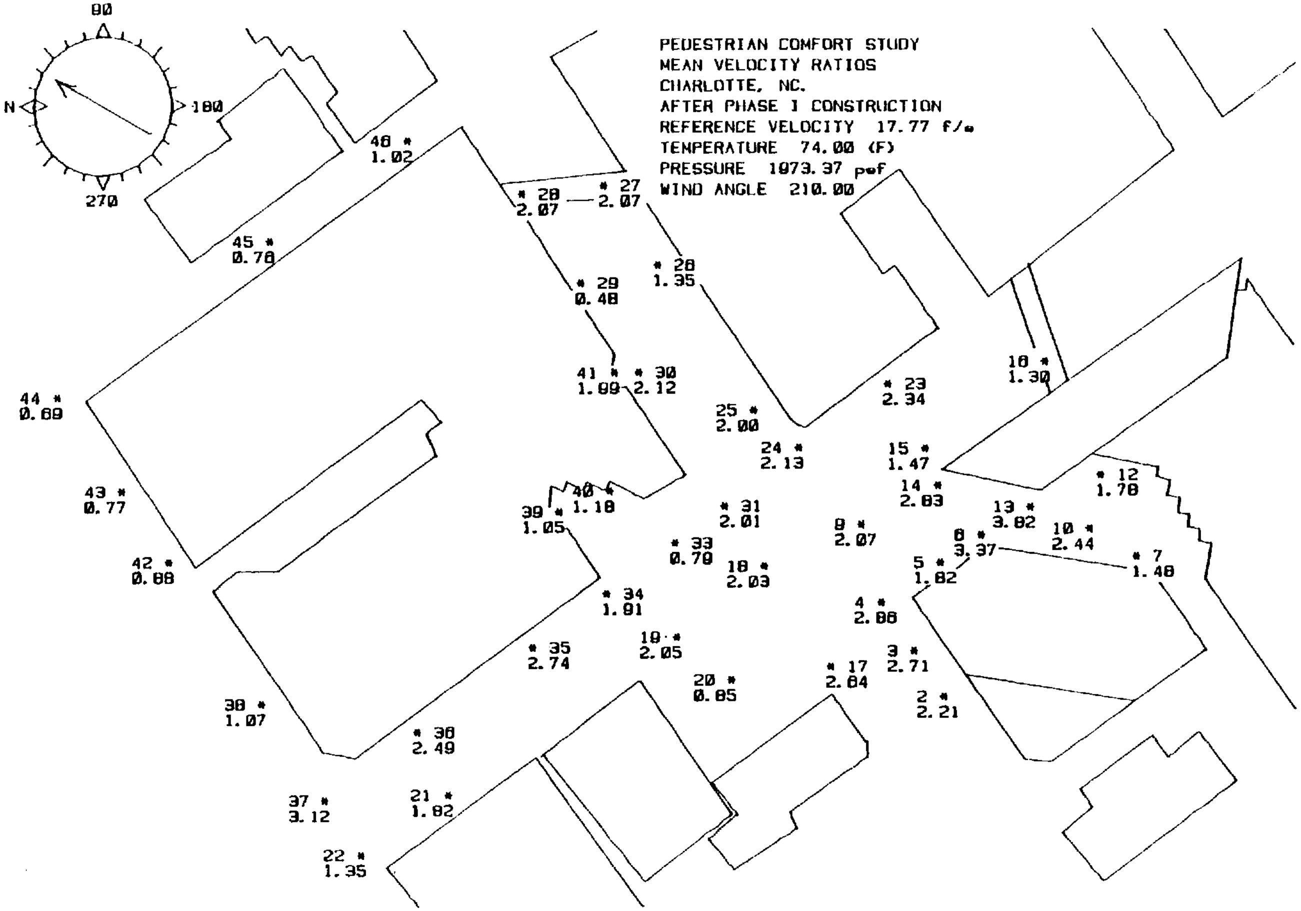
WIND ANGLE 180.00


PEDESTRIAN COMFORT STUDY
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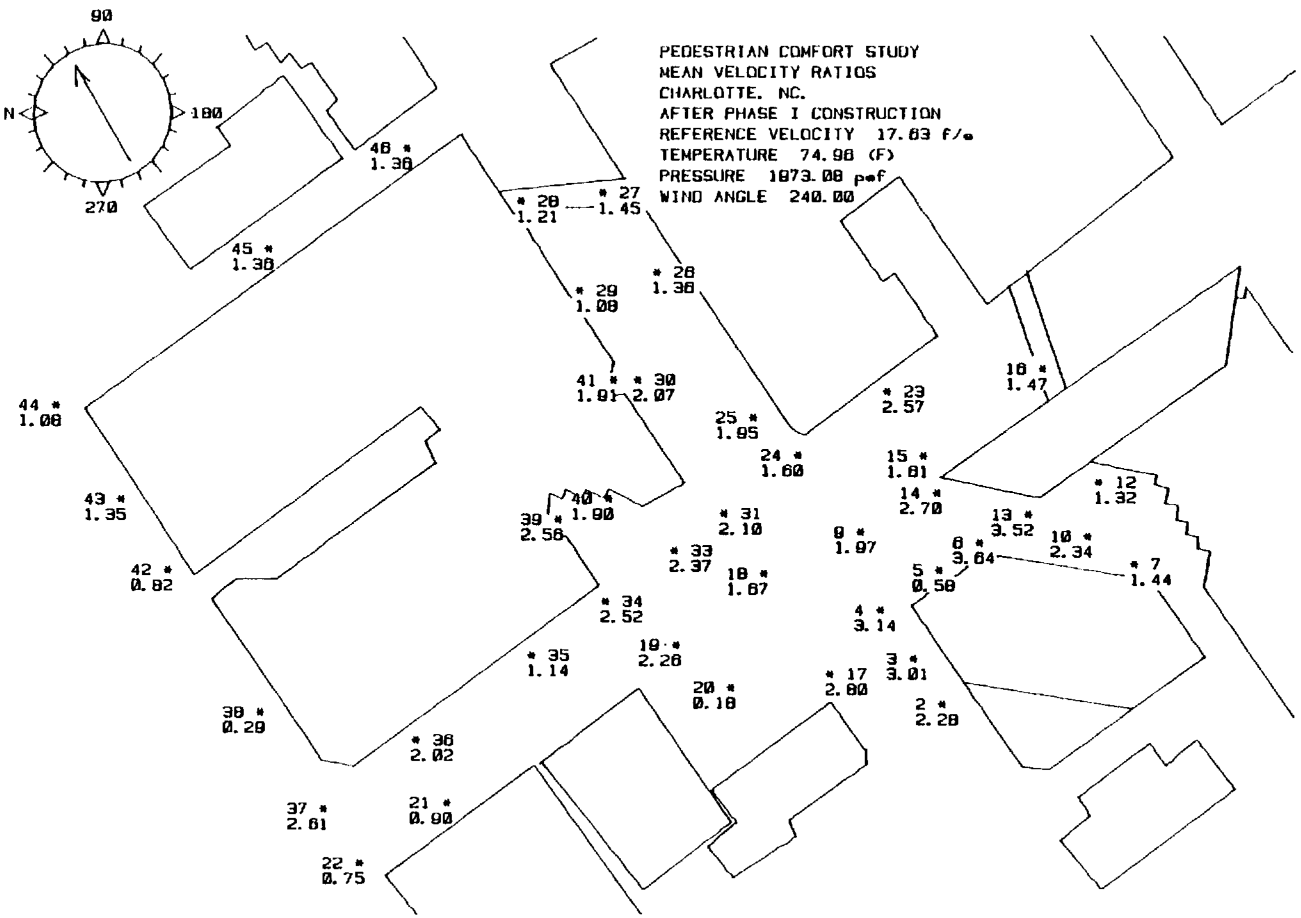
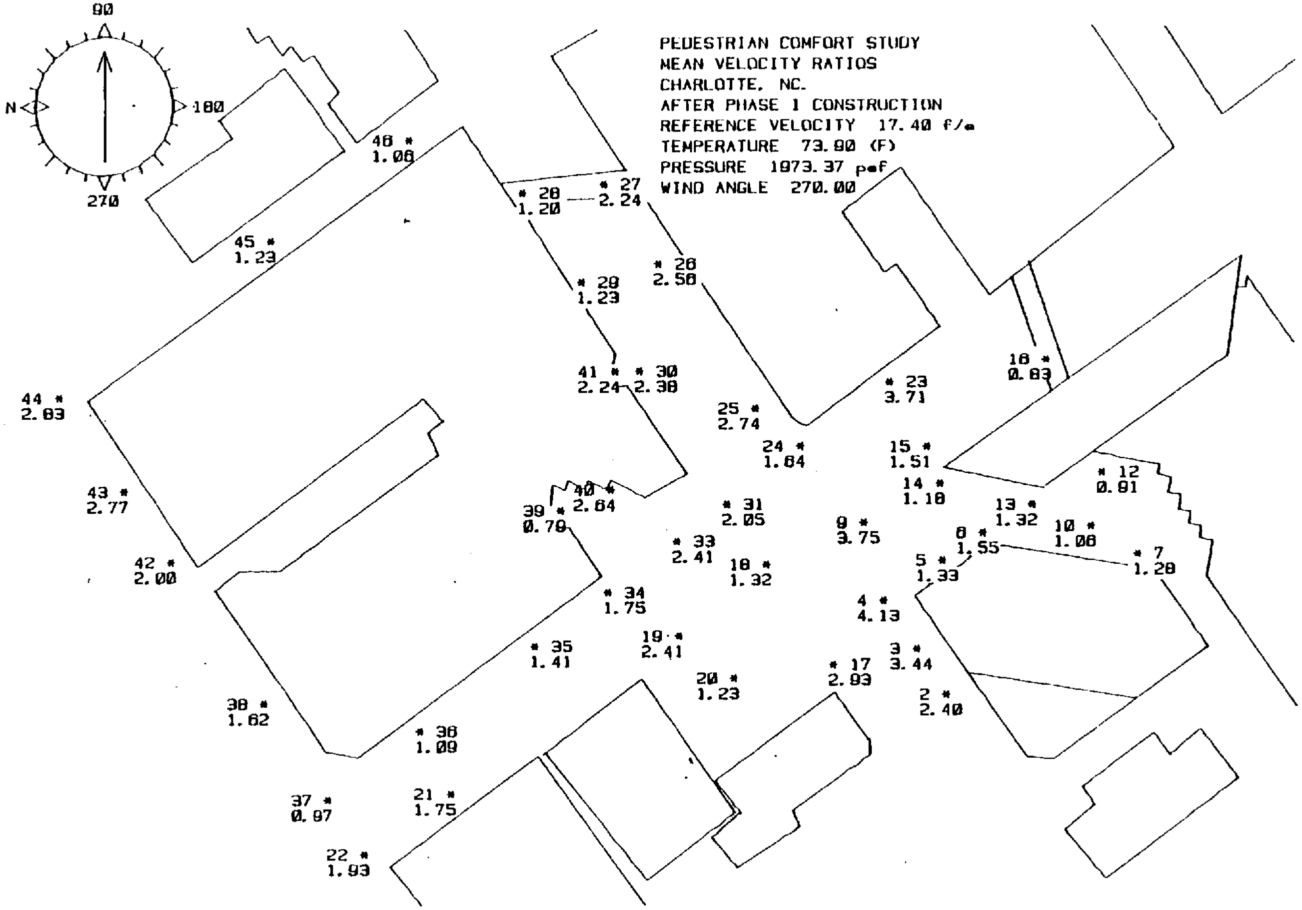
PRESSURE 1973.37 psf
WIND ANGLE 210.00



PEDESTRIAN COMFORT STUDY
MEAN VELOCITY RATIOS
CHARLOTTE. NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.63 f/s
TEMPERATURE 74.98 (F)
PRESSURE 1873.08 psf
WIND ANGLE 240.00



PEDESTRIAN COMFORT STUDY
MEAN VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
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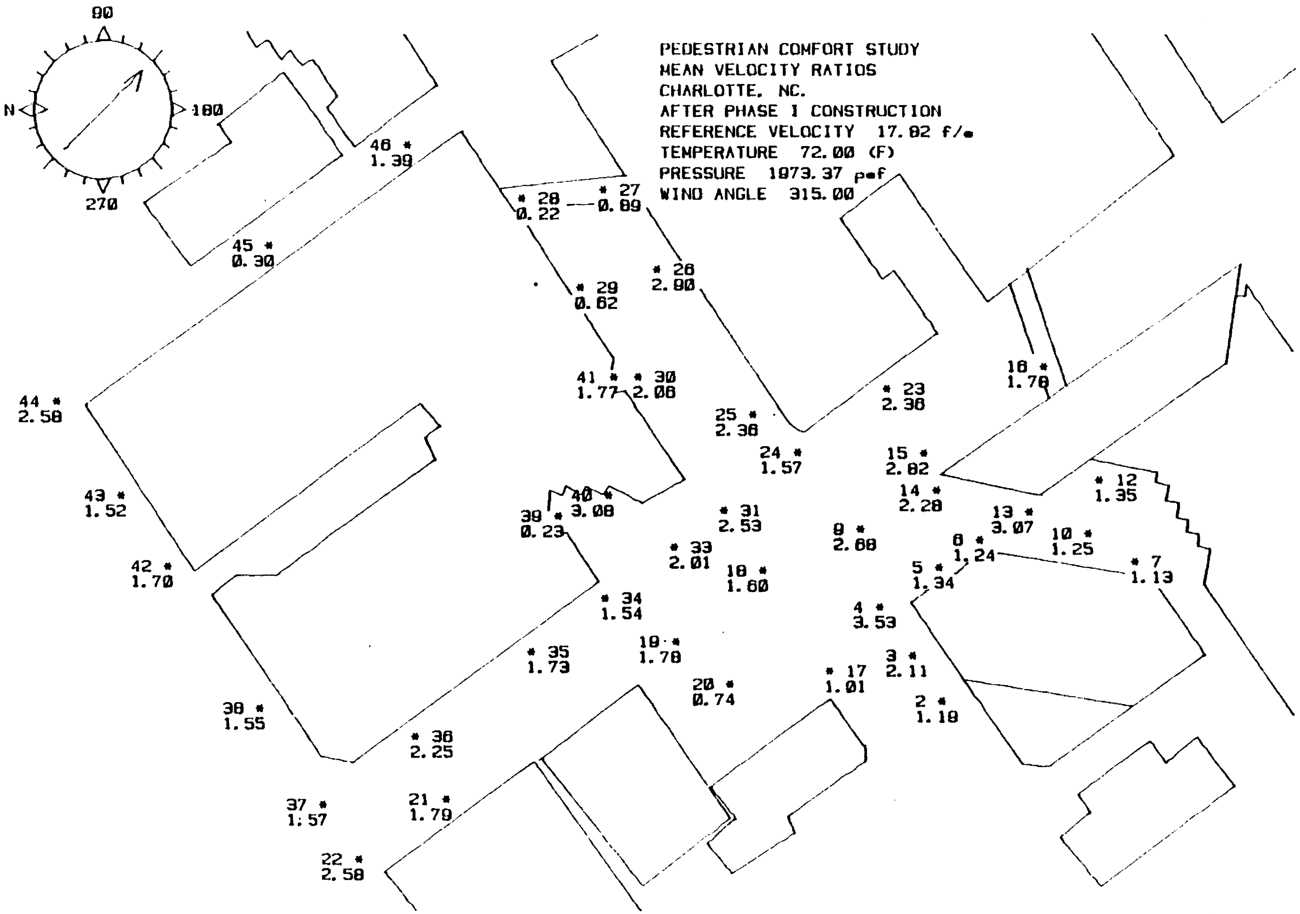
TEMPERATURE 73.90 (F)
PRESSURE 1973.37 psf
WIND ANGLE 270.00



PEDESTRIAN COMFORT STUDY
MEAN VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.82 f/s
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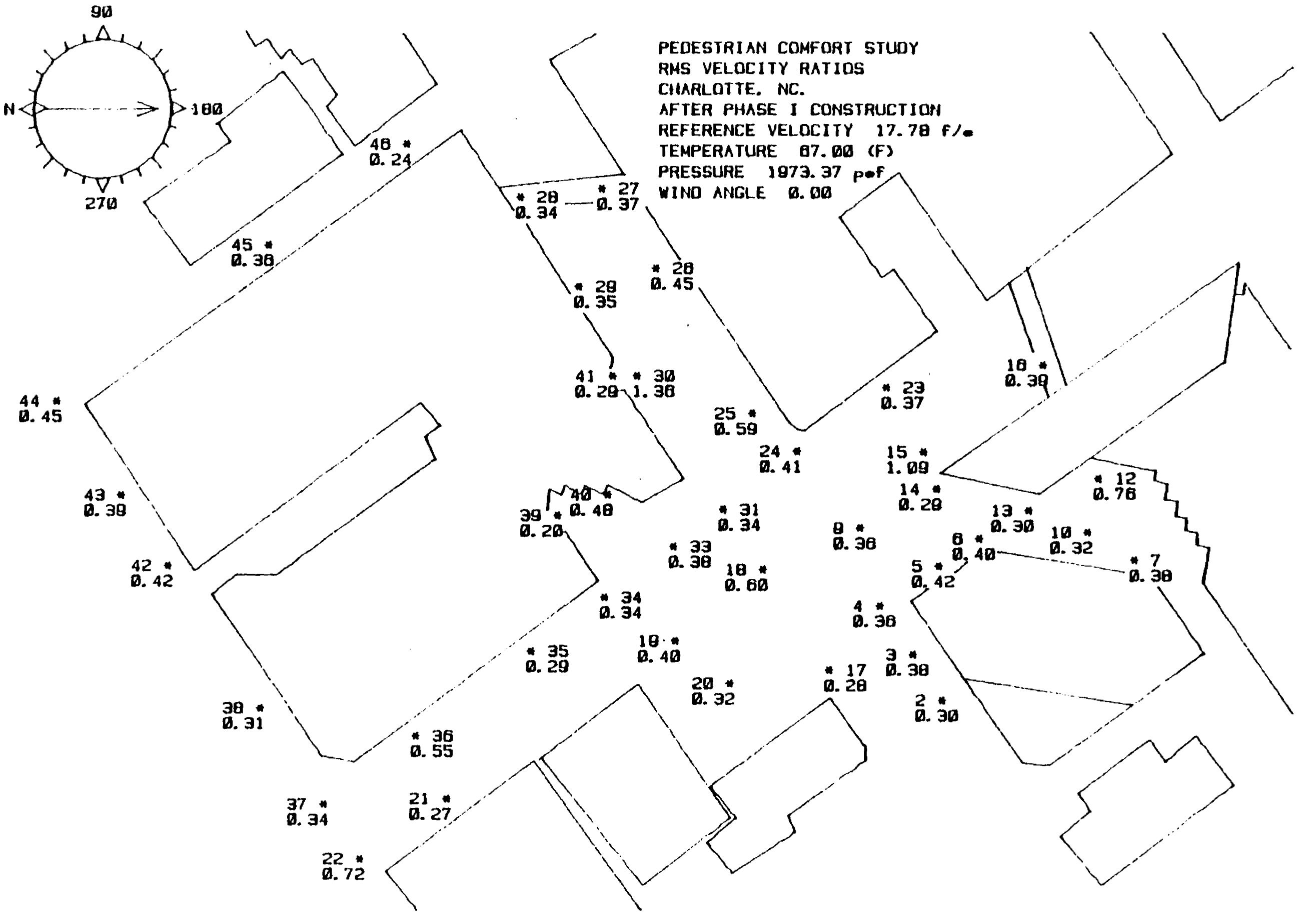
APPENDIX C

RMS VELOCITY (SPEED) RATIOS



PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
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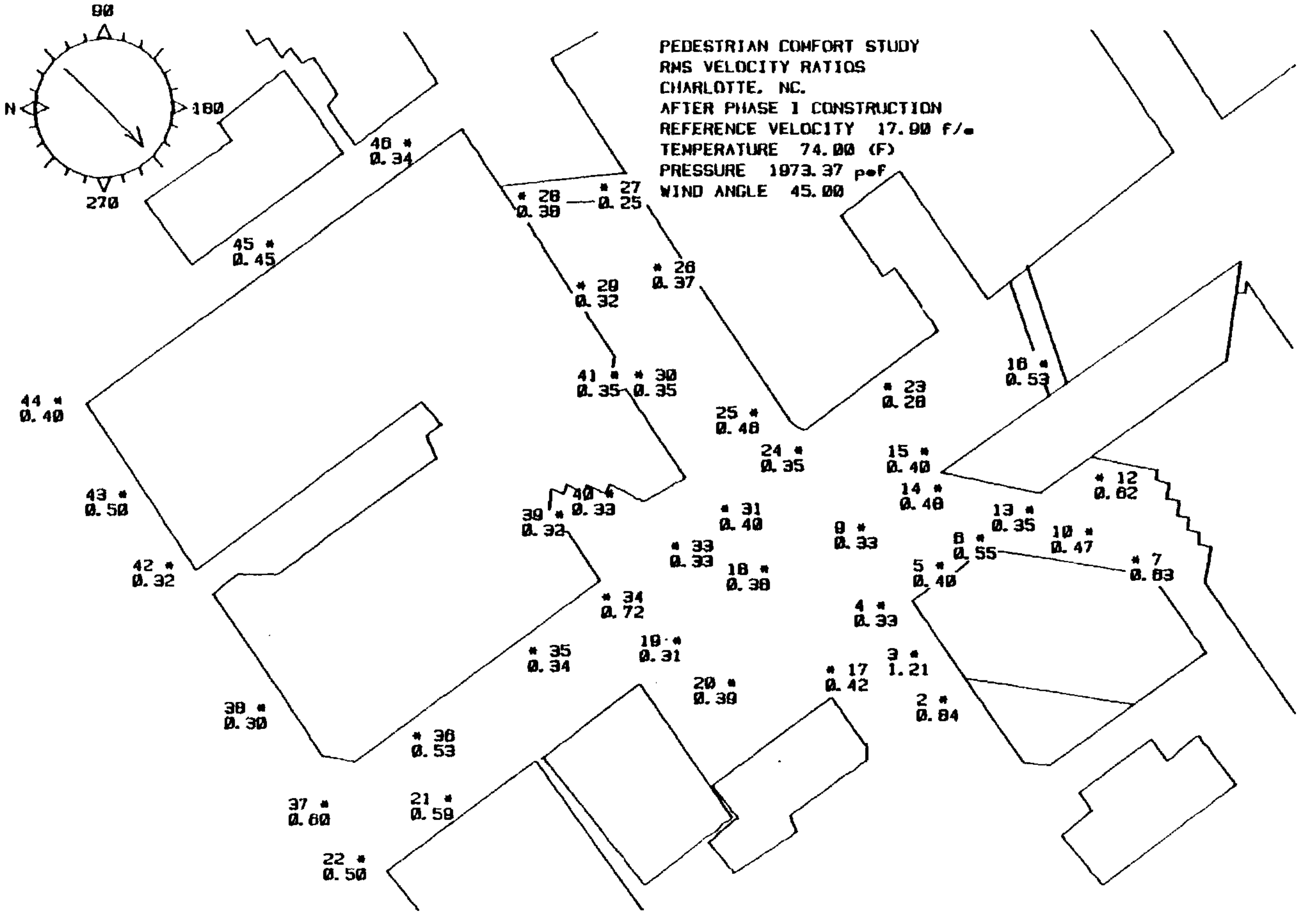
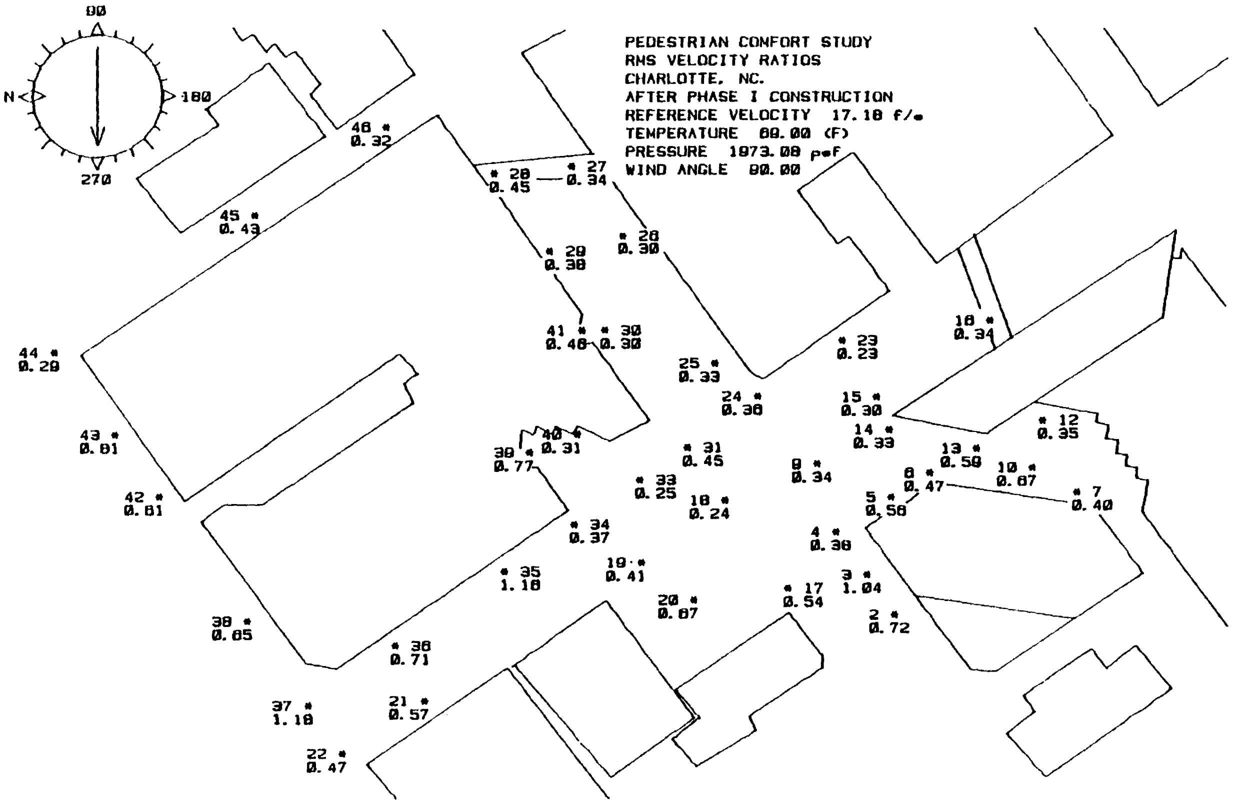
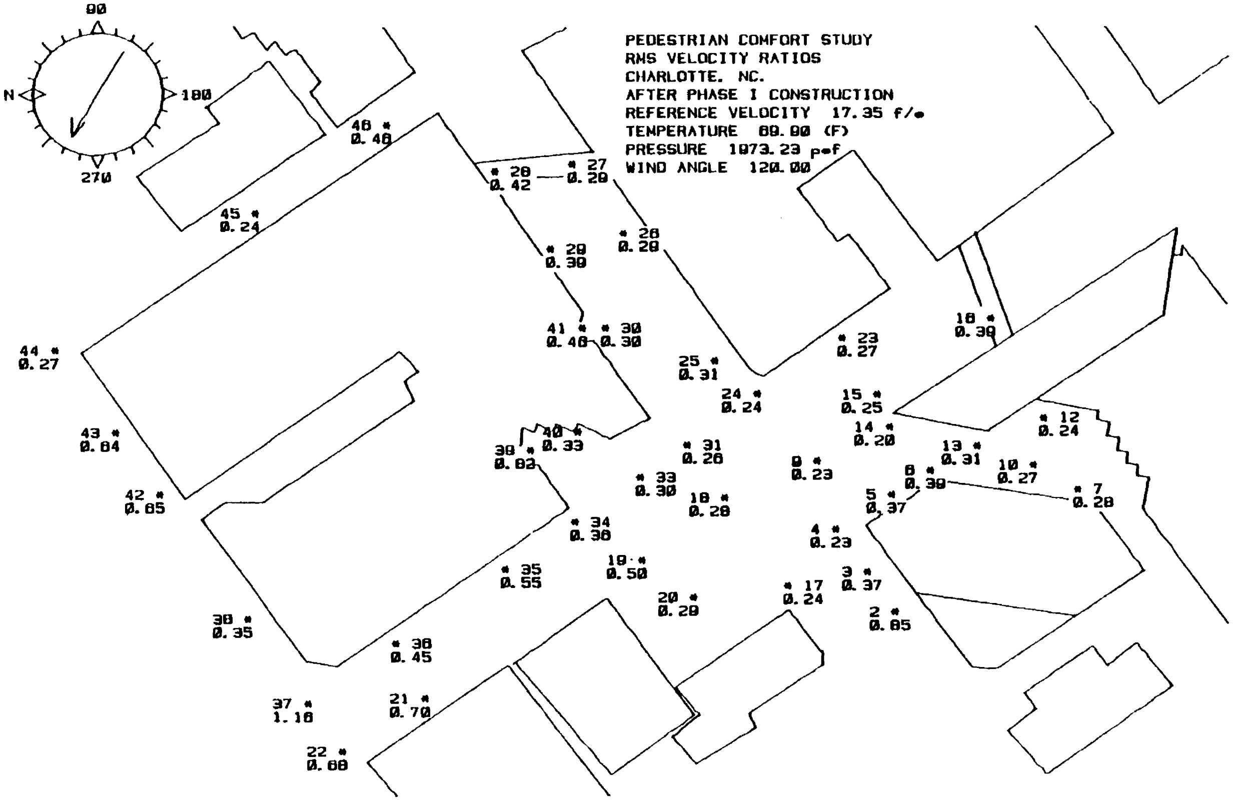
PRESSURE 1973.37 psf
WIND ANGLE 0.00



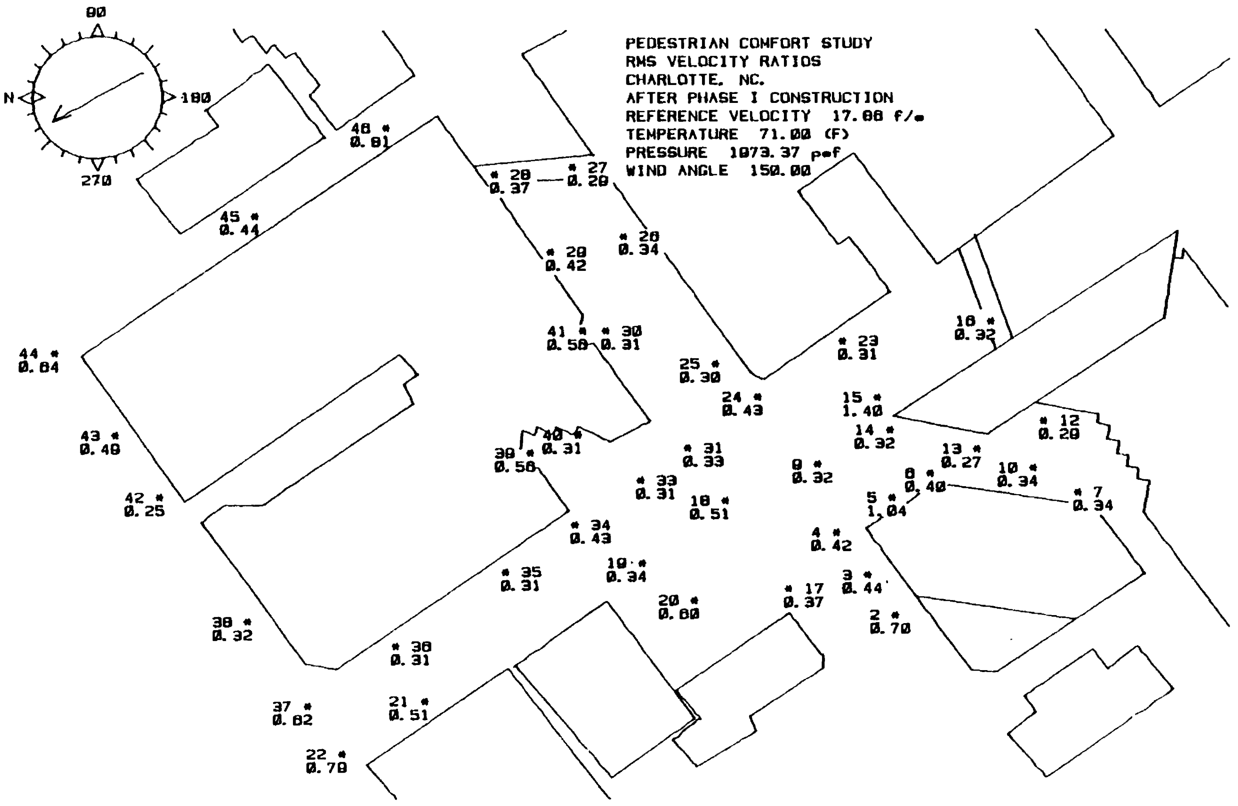
PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.90 f/s
TEMPERATURE 74.00 (F)
PRESSURE 1973.37 psf
WIND ANGLE 45.00
90
N
180
270
46 * 0.34
45 * 0.45
44 * 0.40
43 * 0.50
42 * 0.32
28 * 0.38
27 * 0.25
26 * 0.37
29 * 0.32
41 * 0.35
30 * 0.35
25 * 0.48
24 * 0.35
23 * 0.28
16 * 0.53
15 * 0.40
14 * 0.48
12 * 0.62
13 * 0.35
40 * 0.33
39 * 0.32
31 * 0.40
9 * 0.33
8 * 0.55
10 * 0.47
7 * 0.83
33 * 0.33
18 * 0.38
5 * 0.40
34 * 0.72
4 * 0.33
19 * 0.31
35 * 0.34
3 * 1.21
17 * 0.42
20 * 0.39
2 * 0.84
38 * 0.30
36 * 0.53
37 * 0.60
21 * 0.59
22 * 0.50



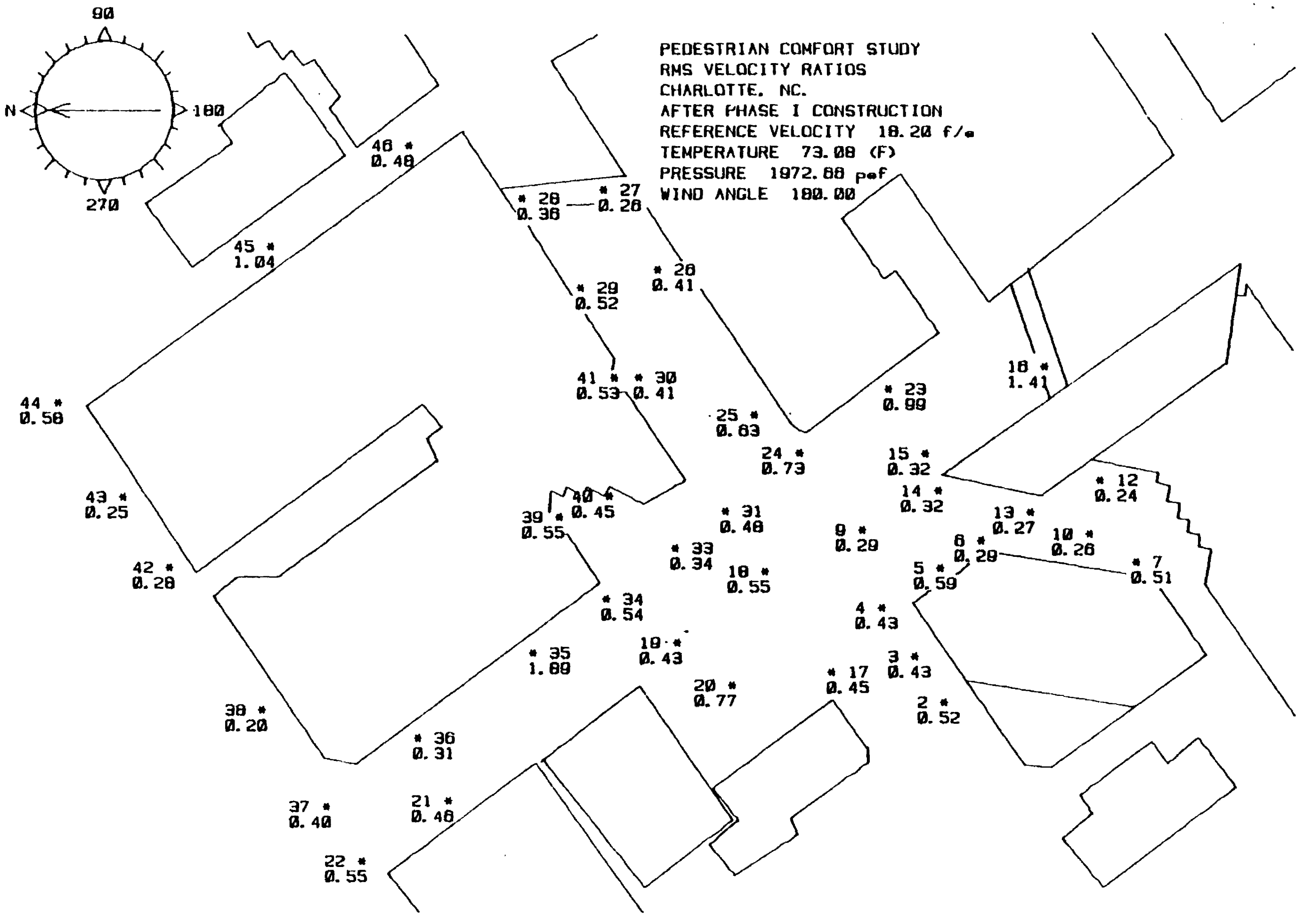
PEDESTRIAN CONFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.18 f/s
TEMPERATURE 68.00 (F)
PRESSURE 1873.08 psf
WIND ANGLE 90.00



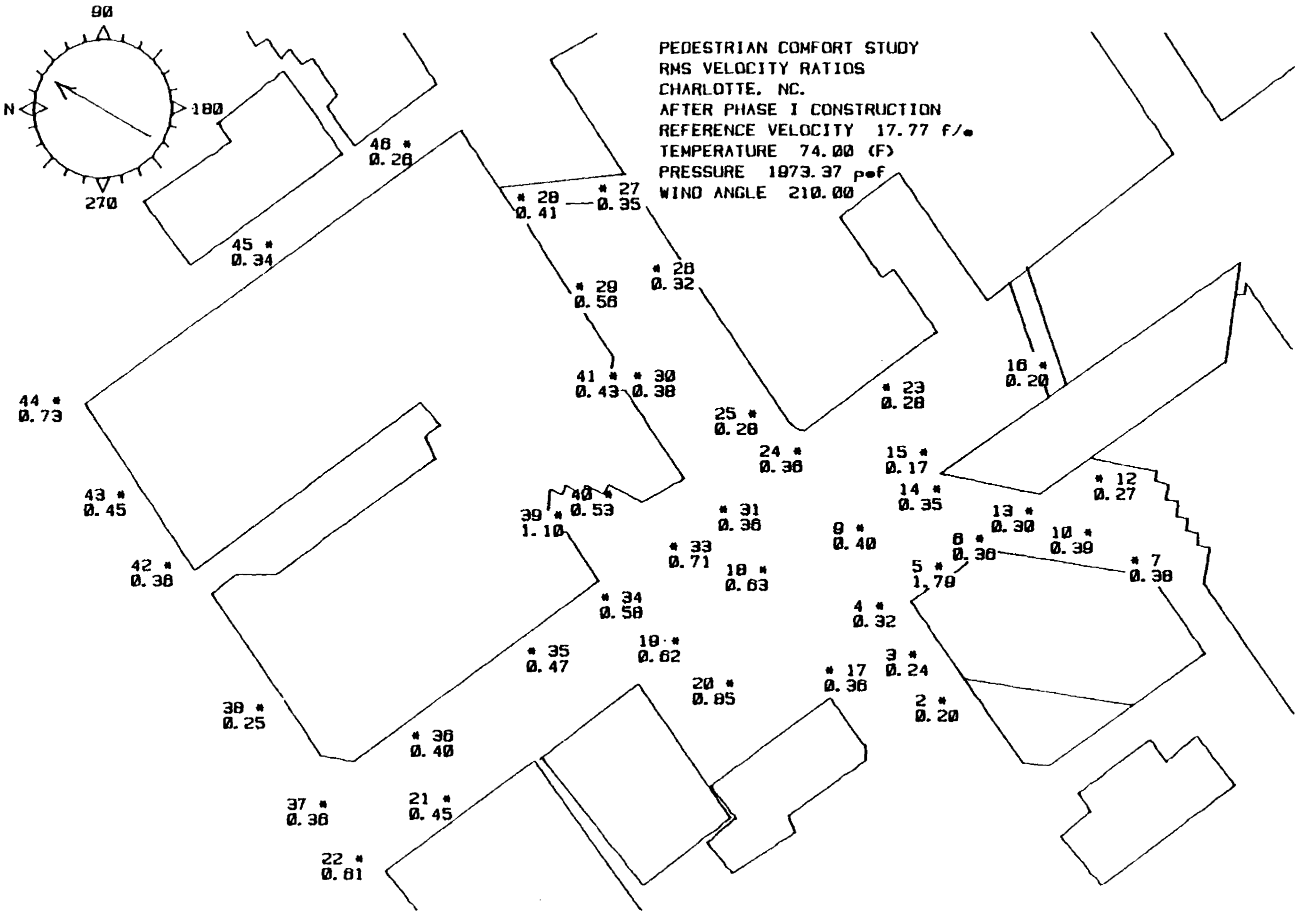
PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE. NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.35 f/s
TEMPERATURE 69.00 (F)
PRESSURE 1073.23 psf
WIND ANGLE 120.00



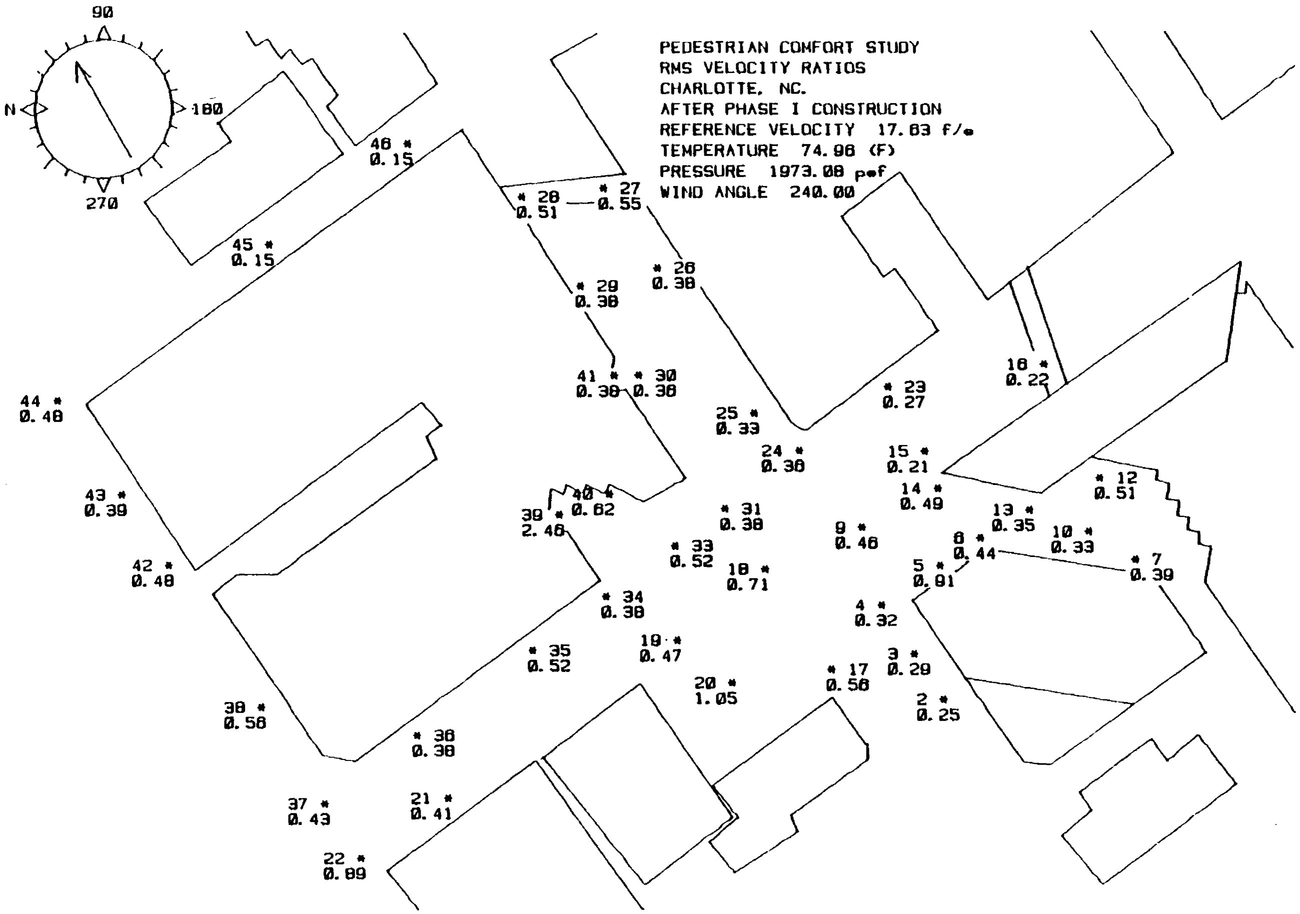
PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.08 f/s
TEMPERATURE 71.00 (F)
PRESSURE 1073.37 psf
WIND ANGLE 150.00



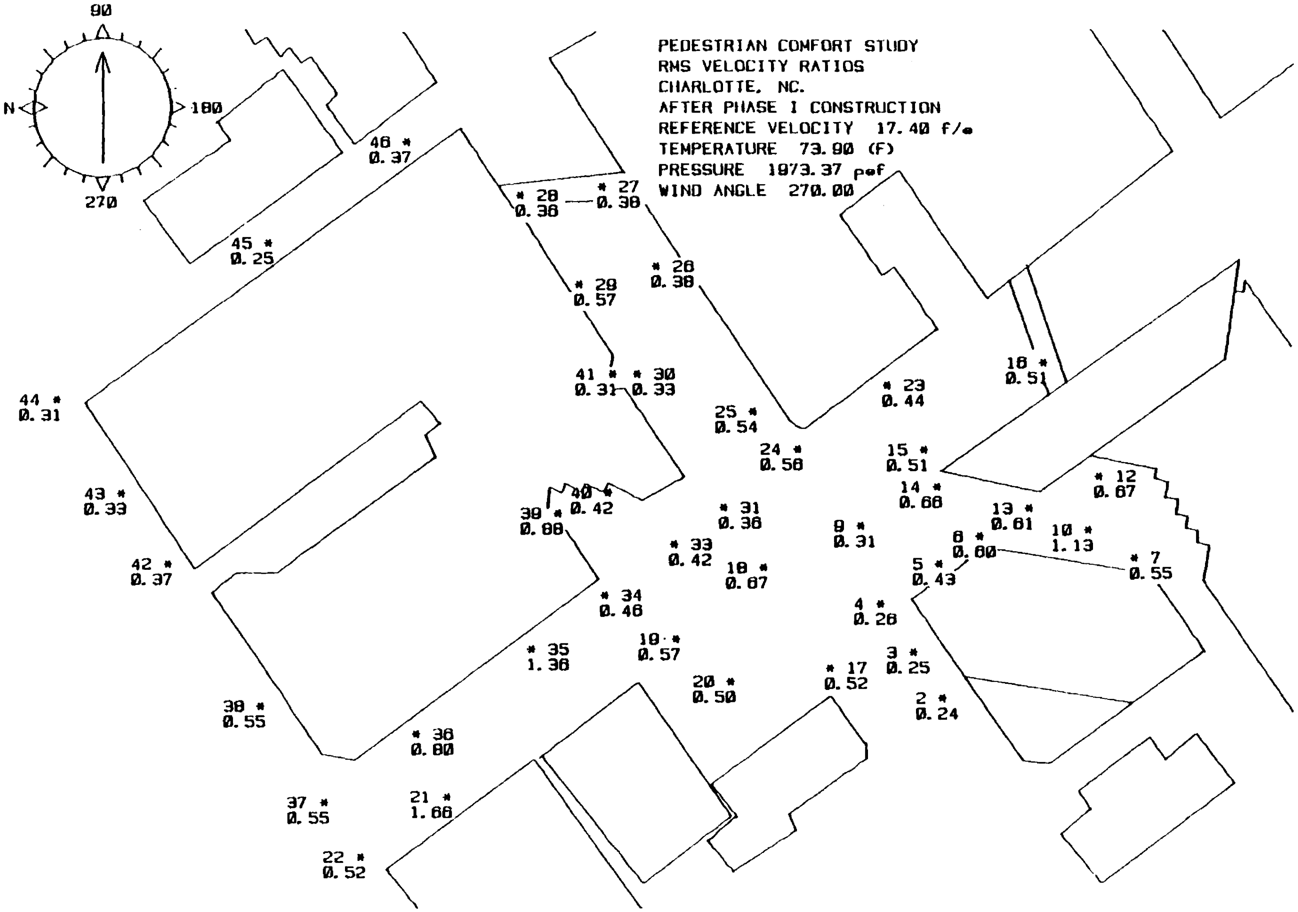
PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 18.20 f/s
TEMPERATURE 73.08 (F)
PRESSURE 1972.88 psf
WIND ANGLE 180.00



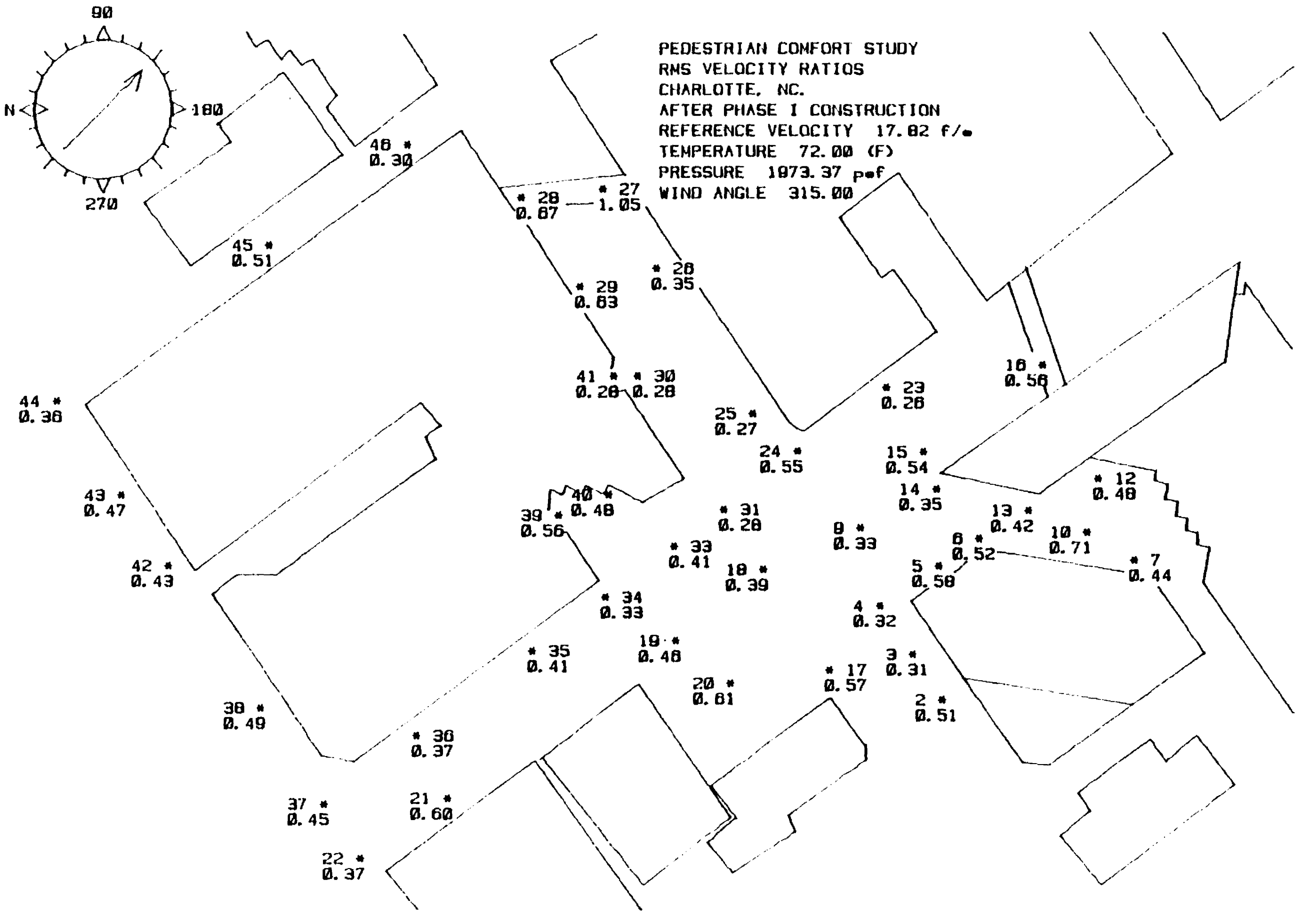
PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE. NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.77 f/s
TEMPERATURE 74.00 (F)
PRESSURE 1073.37 psf
WIND ANGLE 210.00



PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.63 f/s
TEMPERATURE 74.96 (F)
PRESSURE 1973.08 psf
WIND ANGLE 240.00



PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.40 f/s
TEMPERATURE 73.90 (F)
PRESSURE 1973.37 psf
WIND ANGLE 270.00



PEDESTRIAN COMFORT STUDY
RMS VELOCITY RATIOS
CHARLOTTE, NC.
AFTER PHASE I CONSTRUCTION
REFERENCE VELOCITY 17.82 f/●
TEMPERATURE 72.00 (F)
PRESSURE 1873.37 p●f
WIND ANGLE 315.00

A STUDY OF THE WIND ENVIRONMENT IN A CITY CENTER

by

Jamal M. Elzebda

(ABSTRACT)

The nature and effects of windy conditions in a city are first discussed, recording meteorological data are introduced, and existing criteria for the acceptability of a wind environment with regard to pedestrian comfort are described. General features of wind-tunnel techniques are reviewed. A study of the wind environment at a specific site, the center of Charlotte, NC, is made by combining meteorological data taken at a nearby airport with results obtained from wind-tunnel tests conducted on a model of that specific site. Finally, conclusions are drawn concerning the consistency and applicability of currently used pedestrian comfort criteria.